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ABSTRACT

A total of 1329 bulk cutting samples from deep wells in Denmark were analysed for U, Th and K by laboratory gamma-ray analysis. Contamination of the samples by drilling mud additives, mud solids and fall down was studied by means of a wash down experiment and by comparison with the total gamma-ray response from wireline logging. It is concluded that the inorganic geochemistry on bulk cutting samples must be applied with great caution. The data are useful for geochemical characterization of well sections and for regional geochemical correlation.

Radioelement abundance logs and radioelement ratio logs are presented from 3 wells in the Danish Subbasin and 2 wells in the North German Basin. The radioelement geochemistry is discussed for the successive lithostratigraphical units and a reference radio element profile is established for the central part of the Danish Subbasin. Finally, a model describing the relationship between common lithofacies and their U content and Th/U ratio is suggested. The model deliniates the depositional environment and the relative distances to the provenance areas.

(Continued on next page)

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It is concluded that

1) Uranium is mobile during deposition, but since then it is fixed by stable mineral phases at depth.

2) Thorium reflects source area characteristics and that any available ions are readily adsorped by clay minerals. Thorium anomalies may thus serve as lithostratigraphical markers.

3) Potassium occurs in unstable rock forming mineral phases. The present distribution is controlled not only by the clastic mineral assemblage, but also by the diagenetic processes through geologic time.

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CONTENTS

1. INTRODUCTION

The gamma ray wireline log has for more than 30 years been a standard tool in well logging. The tool measures the total natural radioactivity of the formation intersected by the well. The gamma radiation is recorded within a certain energy interval which is typically from 0.3 to 3 MeV. The natural radioactivity from potassium, uranium and thorium bearing minerals varies in accordance with the mineral assemblage in the sedimentary rock type. The gamma log is therefore used as a primary "lithological log", and quantitatively as an indicator of the shale content.

Interpretation of the total gamma-ray log (GR log) possesses problems when several radioactive minerals are present in a rock. If the radioactivity of a sandstone is due to a mica and K-feldspar content rather than a clay content, the shale volume may be erroneously calculated and the shale effect on the log suite misinterpreted.

The gamma-ray spectral log (NGS log) which has be increasingly used since 1975 makes up for some of the difficulties as it enables the interpreter to distinguish between log responses from U, Th and K bearing minerals (Suau & Spurlin 1982, Marett et al. 1976). The logging industry has presented a number of cross plots, eg. the photoelectric effect Pe from the Litho-Density log (LDT) versus the Th/K ratio, which provide a direct identification of the predominant radioactive minerals. The NGS log is comparatively expensive and its use is often restricted to reservoir intervals.

During 1979-1985 five deep exploration wells were drilled in Denmark with the purpose of storage of natural gas and exploitation of low temperature geothermal energy. None of these were logged with the natural gamma-ray spectral tool. The wells intersected Mesozoic stratigraphic intervals of considerable thicknesses in the Danish sedimentary subbasin and in the North German Basin. Lithologically the wells encompass a very large range of sedimentary rocks with respect to both composition and depositional environment.

The purpose of the present radiometric study was to present the typical variations of naturally occurring radioactive minerals within the Mesozoic and Cainozoic sequences in the Danish Subbasin and the North German Basin. The radiometric profiles are constructed on the basis of gamma-ray analyses of bulk cutting samples. They are intended to serve as preliminary geochemical reference profiles for major lithostratigraphical units. They may improve the lithological, stratigraphical and geochemical interpretation of all intervals which have not been or will not be logged by gamma-ray spectrometry.

Downhole in-situ analysis is influenced by attenuation of the gamma rays in the drilling fluids and by radioactive constituents in the mud. These constituents may be partly mud chemicals and partly solid particles from the penetrated formations. Similarly the bulk cutting samples are to a varying degree contaminated by mud chemicals and by "fall down" from the shallower formations in the hole. These effects have been studied and quantified in a separate laboratory experiment which is summarized in Chapter 3.

A total of 1329 samples have been analysed from the wells Aars-1, Farsø-1, Thisted-2, Tønder-4 and Tønder-5. The location of these wells is shown on the map in Fig. 1. Table 1 lists the depths and the number of samples analyzed from the individual wells.

Table 1: Investigated wells and sample intervals

Well	Total depth (mbKB)	Analysed interval (m)	Nos. of analyses
Aars-1	3401	2004-2980	193
Farsø-1	2952	60-2949	203
Thisted-2	3290	228-2680	340
Tønder-4	1870	90-1870	320
Tønder-5	1915	165-1915	273

1.1 Geochemical reactions in sediments

Inorganic geochemical processes including both major elements and trace elements in sedimentary rocks are controlled by the interactions between formation water and host rock through geological time. Pressure, temperature and host rock geochemistry define the regime for the alteration processes which during diagenesis dissolve and precipitate minerals in a series of complex reactions.

In order to take advantage from geochemical data it must be possible to relate the analytical results to geochemical characteristics in the provenance area for the sediments, the depositional environment and the subsequent processes during the burial history.

Dissolution of minerals during diagenesis may be either congruent or incongruent (Althaus et al. 1985). In incongruent dissolution the liquid (formation water) is enriched in alkalies and incompatible trace elements whereas elements like Fe, Al and Si are fixed in a solid layer on mineral surfaces. In congruent dissolution the stoichiometric proportions between elements in the aqueous and solid phases are equal. Laboratory experiments by Beusen et al. (1985) suggest that incongruent dissolution is common at ambient condition. Thus, removal of formation water by e.g. compaction or by dynamic drive forces will result in gradual change in the bulk chemical composition of the water-rock system.

The present day geochemistry of a sedimentary rock is therefore partly inherited from the source area and partly changed by later processes into a generally more simple (mature) chemical composition.

To the extent K, U and Th bearing minerals in a sediment interact with the formation water, one would expect a decrease in the amount of these elements with increasing geological time within the solid phase.

The concept of the existence of the non-isochemical regime with time is important, and it will be demonstrated in the data presentation chapter that trends in the element concentration plots result from chemical instability between rocks and formation water. Ultimately the dissolved elements may theoretically precipitate by a large scale "hypogene" enrichment process at shallower levels.

1.2. Geochemistry of U, Th and K

The distribution of U, Th and K in sedimentary rocks and minerals is primarily controlled by the provenance of the clastic components and secondly by the physical and chemical stability of these components in the sedimentary environment. Typical geochemical values for U, Th and K in major rock types and minerals are listed in Table 2 (Fertl, 1979). To the extent these controlling factors are known, it may be possible to evaluate the depositional environment and the stability regime on the basis of radiometric analysis, provided that the geochemistry of the source materials is uniform. Radioelement geochemistry is therefore applicable in lithostratigraphical evaluation of rock type, source area characteristics, depositional environment and diagenesis. A review of the general geochemistry of U, Th and K in sedimentary rocks is presented below.

Table 2: Potassium (K), Uranium (U) and Thorium (Th) distribution in common rocks and minerals (modified after Pertl, 1979)

	K (%)	U (ppm)	Th (ppm)
Accessory Minerals			
Allanite		30-700	500-5000
Apatite		5-150	20-150
Epidote		20-50	50-500
Monazite		500-3000	2,5x10-20x10
Sphene		100-700	100-600
Xenotime		500-3.4x10	Low
Zicron		300-3000	100-2500
Basalt			
Alkali basalt	0.61	0.99	4.6
Plateau basalt	0.61	0.53	1.96
Alkali olivine basalt	<1.4	<1.4	3.9
Tholeiites (orogene)	<0.6	<0.25	<0.05
(non orogene)	<1.3	<1.5	<1.5
Carbonates			
Range (average)	0.0-2.0 (0.3)	0.1-9.0(2.2)	0.1-7.0 (1.7)
Calcite, chalk, limestone, dolomite (all pure)	<0.1	<1.0	0.5
Clay Minerals			
Bauxite		3-10	10-130
Glauconite	5.08-5.30		
Bentonite	<0.5	1-20	6-50
Montmorillonite	0.16	2-5	14-24
Kaolinite	0.42	1.5-3	
Illite	4.5	1.5	
Mica			
Biotite	6.7-8.3		<0.01
Muscovite	7.9-9.8		<0.01
Feldspars			
Plagioclase	0.54		<0.01
Orthoclase	11.8-14.0		<0.01
Microline	10.9		<0.01
Gabbro (mafic igneous)	0.46-0.58	0.84-0.9	2.7-3.85
Granite (silicic igneous)	2.75-4.26	3.6-4.7	19-20
Granodiorite	2-2.5	2.6	9.3-11
Oil Shales, Colorado	<4.0	up to 500	1-30
Phosphates		100-350	1-5
Ryolite	4.2	5	
Sandstones, range (av.)	0.7-3.8 (1.1)	0.2-0.6 (0.5)	0.7-2.0 (1.7)
Silica, quartz, quartzite, (pure)	<0.15	<0.4	<0.2
Shales			
"Common" Shales	1.6-4.2	1.5-5.5	8-18
Schist (biotite)		2.4-4.7	13-25

1.2.1. Uranium (U)

Uranium does not constitute rock forming minerals but occurs together with Th as a trace element in accessory minerals, as UO_2 precipitates, and as a chemical absorption element. It is a mobile element which is soluble in the U^{+6} state (oxidizing conditions) and insoluble in the U^{+4} state (reducing conditions). Uranium forms chemical ion complex bonding with Fe, Ca and P, and positive correlation with these elements is often found. Uranium is absorbed on organic matter, and on colloided Fe-oxid/hydroxide coatings on mineral grains.

Absolute variations in the amount of U therefore reflect the rock type and the redox condition during deposition. The relative proportions between U and associated elements (Ca, Fe, P, Th) are indications of source area characters and post depositional diagenetic processes. The association of U with organic matter may be used in the definition of hydrocarbon source beds.

1.2.2. Thorium (Th)

Like uranium, thorium does not constitute rock forming minerals, whereas it is a common trace element in most geological environments.Heavy accessory minerals are generally rich in Th (Table 2) and also clay minerals absorb Th and are characterized by high trace level concentrations. It is important for the interpretation of spectral logs that the Th/K ratio is higher in clay bearing sandstones than in micaceous sandstones, which again is higher than the Th/K ratio in feldspathic sandstones.

Thorium is geochemically less mobile than Uranium, and the solubility of Th is not influenced by the redox potential. The refractory character of most thorium bearing minerals means that thorium geochemically provides primary information about rock composition and source area geology.

1.2.3. Potassium (K)

Potassium is a major element in many rock forming minerals and as such K is an important indicator of mineralogical composition, both in the source areas and in the derived sediments. The most common K-bearing minerals in sedimentary rocks are K-feldspar, muscovite, illite and glauconite. The potassium content of feldspathic sandstone and claystone varies typically from 0.5 to 4% and 1.5 to 5% respectively. The stability of the potassium minerals is strongly temperature and pressure dependent and thus subject to alteration during diagenetic processes. Besides constituing excellent lithological markers, changes in the K-content with depth may be an important reflection of dissolution or neoformation of K-minerals.

1.3. Geological setting

1.3.1. Danish Subbasin

The wells Aars-1, Farsø-1 and Thisted-2 are situated in the Danish Subbasin which forms the eastern extension of the Norwegian-Danish Basin (Fig. 1). Aars-1 and Farsø-1 are located in the central part of the basin, whereas Thisted-2 is more marginal and reaches the deepest stratigraphical level. The depositional history of the sedimentary Mesozoic rocks is reported in several publications, e.g. Michelsen (1978), Bertelsen (1980). The chronostratigraphical and lithostratigraphical history is outlined in Figure 2.

The evolution of the Danish Subbasin during Mesozoic time was reviewed by Surlyk (1980). The sedimentary evolution encompasses several transgressive and regressive periods which may be deducted from the lithology column in Figure 2. The relative changes in sea level resulted in an interbedded series of continental red beds, marine pelagic sediments and coarser clastic sediments deposited in continental and marginal marine environments. Source areas for the clastic materials were the fault controlled Ringkøbing-Fyn High to the south and the Fennoscandian Shield to the

north and east. The depocenters in the Danish Subbasin were located in North Jutland but changed their position somewhat during geological time. Differential subsidence was partly controlled by the development of salt domes and salt pillows on a local scale.

1.3.2. North German Basin

The wells Tønder-4 and Tønder-5 are situated in the northern part of the North German Basin. The distance between the wells is approximately 5 km. Although the sediments wedge out against the Ringkøbing-Fyn High to the north, they may be lithostratigraphically correlated with deposits situated more centrally in the basin. The Triassic deposits are continental redbeds with intercalated evaporite rocks. The source area for the clastic materials is the Ringkøbing-Fyn High to the north. The Jurassic and Upper Triassic deposits are absent in the south Jutland area, and the Oddesund Formation (Figure 2) is overlain by Lower Cretaceous marine deposits.

The Tønder wells are situated on a structural high controlled by a pillow of Zechstein salt. This structural position, however, has only little significance for the stratigraphical understanding and the interpretation of the radiometric data.

2. LABORATORY GAMMA-RAY ASSAY METHOD

The sample material utilized in this study was a series of bulk cutting samples recovered from the shale shaker on each drilling site. Most of these samples represented a drilling interval of five meters, which accordingly is the approximate unit step length in the geochemical logs provided by analysing the samples. The analytical method used was that of sealed-can gamma-ray spectrometry. In this method the concentrations of U, Th, and K in the sample material are estimated by recording the natural gamma-ray spectrum for the material. Sealing a sample by enclosing it in a metal can prevents contamination of the gamma-ray spectrometer and makes it possible to attain an equilibrium concentration of radon gas within the sample volume.

2.1. Experimental procedure

The cutting samples, which were still greasy after having been stored in canvas bags for several years, were smeared and compressed into metal cans which had an inner diameter of 72 mm and were 47 mm deep. A series of typically 20 to 30 samples was left uncovered for 24 hours in a ventilated oven kept at 105°C. This operation converted the assay material into a dry, more or less solidified mass whose weight was determined by subtracting the weight of an empty can. The cans were then sealed by top lids added by means of a canning machine. Most of the samples analysed weighed between 200 and 300 grams.

The laboratory gamma-ray spectrometer, which is located in a concrete enclosure at Risø National Laboratory, is shown in Figure 3. The rectangular frame on the left is a sample changer in which the samples are stored in a vertical tray that offers space for up to 50 samples. The cylinder on the right is a massive lead shield which houses a 127 x 127 mm, horizontally mounted sodium-iodide gamma-ray detector. There is a 75 mm long light guide of sodium iodide without thallium activator between the detector and its associated photomultiplier tube. This special design largely

eliminates background counts due to the potassium in the glass envelope of the photomultiplier. To protect the detector assembly against dust and atmospheric radon, there is a dividing wall of plexiglass between the detector compartment and the sample compartment of the spectrometer. Access to the sample compartment is provided by an excentric sample-changer wheel. Once the sample tray has moved into position, horizontally and vertically, a robot arm pushes the selected sample can into an adjacent recess on the periphery of the sample-changer wheel. The wheel then makes a quarter of a revolution in the clockwise direction, thereby positioning the sample centrally in front of the gamma-ray detector. When the sample spectrum has been recorded, the wheel turns back again, and the sample is withdrawn to its position in the sample tray by activation of a magnetic head on the robot arm. This mechanical cycle is terminated by the selection of a new sample, effectuated by a horizontal or vertical displacement of the sample tray.

The multichannel analyser of the spectrometer is a Nuclear Data ND-100 interfaced to a diskette drive and to the sample-changer control equipment. The analyser is located outside the enclosure for the spectrometer to keep the latter cool and free from dust. Spectra are recorded using 300 channels which cover the energy range from 0 to 3 MeV, corresponding to 10 keV of radiation energy per channel. The cutting samples were analysed using a counting time of typically 5000 s (1.39 hours) per sample.

2.2. Spectrum Processing Technique

To calculate the radiometric concentrations of U, Th, and K in a sample, a background spectrum is first subtracted from the spectrum recorded with the sample. A new background spectrum is measured two to three times per month using a sample can filled with sugar. Updating the background spectrum at regular intervals eliminates assay error due to long-term variations shown by the content of radon in the air around the spectrometer facility. These

variations are actually quite small, as expressed by an empirical standard deviation of only 2.5% on the total background count rate recorded with the spectrometer. When the background counts in the energy channels have been removed, it can be assumed that the resulting net sample spectrum is produced by the contents of uranium (radium), thorium, and potassium in the sample material.

Having normalized the spectrum to a reference sample weight of 250 grams, the spectrum is now fitted to a linear combination of three calibration spectra which represent the response of the spectrometer to 1 ppm eU, 1 ppm Th, and 1% K in a sample that weighs 250 grams. The letters "eU" stand for "equivalent uranium" and is a reminder of the fact that the uranium is measured indirectly through the gamma-ray emission from the ^{238}U daughter isotopes, ^{214}Bi and ^{214}Pb. In a sealed sample that has been stored for about three weeks before the spectrum recording is performed, ^{214}Bi and ^{214}Pb are in radioactive equilibrium with their gaseous precursor ^{222}Rn (radon) which in turn is a daughter of ^{226}Ra (radium). Thus the unit "ppm eU" is primarily a measure of radium concentration. This consideration may be important from a geochemical viewpoint (due to the different hydrochemistries of radium and uranium), whereas a possible disequilibrium between ^{238}U and ^{226}Ra has no effect on the correlation between gamma-ray analysis and gamma-ray wireline logging.

The three calibration spectra required by the spectral fitting technique are determined by recording the spectra of the six reference samples whose properties are listed in Table 3. Every second reference sample weighs around 225 grams, while those in between weigh roughly 335 grams. These mass differences are produced by varying densities for the reference materials. NBL-102 and NBL-107 are certified radioactive ores intermixed into a light-weight silica matrix ("NBL" is an abbreviation for the New Brunswick Laboratory of the U.S. Department of Energy).

Table 3. Reference samples used to calibrate the spectrometer for radioelement analysis.

Reference sample	Kind of material	Sample weight (g)	ppm eU	ppm Th	%K
U-1	NBL-102	229	1010	-	-
U-2	NBL-74	338	1000	-	-
Th-1	NBL-107	224	41	1000	-
Th-2	NBL-80	336	43	1010	-
K-1	KCl	230	-	-	52.45
K-2	K_2CrO_4	336	-	-	40.27

The two other NBL reference materials, NBL-74 and NBL-80, are heavier because their radioactive particles are embedded in a matrix of powdered dunite. The mass difference between the two potassium reference samples was obtained by preparing these from two potassium salts of highly differing specific gravities (the chloride and the chromate). In using NBL-107 and NBL-80 for thorium calibrations, it is necessary to make a correction for the uranium contents of 41 ppm eU and 43 ppm eU supplied by the monazite used by the NBL to prepare these two Th reference materials. The uranium contents of NBL-107 and NBL-80 were reported by Dickson et al. (1982), and the correction is performed by spectral stripping using the uranium spectra recorded with NBL-102 and NBL-74.

The pairs of pure radioelement spectra recorded with the low-density and the high-density reference materials are utilized in a linear interpolation procedure that provides the three calibration spectra for an analysed sample of almost any weight. This individually performed calibration makes it possible to extend the spectral fitting range down to an energy of 150 keV, so that many of the low-energy peaks in the spectra of U and Th gamma radiation can be exploited in the determination of U and Th sample

concentrations. The fitting method used is a least-squares technique in which each channel count rate is weighed in inverse proportion to the variance which is calculated from the sample counts and the background counts recorded in the channel (Løvborg et al., 1972). To compensate for possible photomultiplier gain drift during the analysis of a sample series, each spectral fit is repeated twenty times using hypothetical gain shifts that vary in steps of 0.1% from -1% to +1%. The fit that produces the smallest chi-square value then automatically selects an optimum set of analysed U-Th-K concentrations.

Figure 4 shows the multichannel spectrum of a cutting sample as well as the spectrum that has been calculated from the background spectrum and the three calibration spectra assigned to the sample. For comparison the background spectrum is also plotted in the figure. In the routinely used procedure to check the analysed sample concentrations of U, Th, and K, the sample spectra and the resulting fitted spectra are plotted by means of the lineprinter of the computer installation.

3. DATA VERIFICATION

To estimate the reliability of radioelement concentrations determined by analysing bulk cutting samples with their contents of mud solids, mud solubles, and fall-down particles, we performed a laboratory separation experiment. In this experiment the solubles contained in three kinds of cutting samples were washed out, while - at the same time - the contents of solids were sieved into coarse, medium, and fine particle fractions whose radioelement concentrations were analysed and compared with those of the original, unwashed sample material. Direct evidence of the degree of matching between radioelement analysis of bulk cutting samples on the one side and gamma-ray wireline logging on the other was obtained by subjecting the radioelement data and the wireline logs from four wells to a statistical analysis. The outcome of the latter was four logs providing the deviation between geochemical logging and wireline logging.

3.1. Laboratory experiment

To obtain sufficient material for a wash-out experiment, the drilling of a hydrocarbon exploration well at Sæby in August 1985 (Well 5710/22-1, Fig. 1) was taken as an opportunity to collect three large cutting samples at various drilling depths: chalk (350 metres), Mesozoic clay (510 to 1005 metres), and Paleozoic coarse clastic rocks (1700 to 1710 metres). The chalk sample (sample 1) and the composite clay sample (sample 2) weighed 17 kg and 8 kg respectively, including contents of drilling mud. Bulk cuttings of the Paleozoic clastic rock were collected in an amount of 33 kg which was divided into three equally sized subsamples, 3A, 3B and 3C.

3.1.1. Procedures

Washing the cuttings was done with assistance from a sample vessel and a laboratory shaker operated with two stacked sieves. The top sieve on which the samples were sprayed with water had a mesh size of 2.4 mm, while the mesh size provided by the bottom sieve

was 0.18 mm. Before starting a wash-out operation, between 1.5 and 2.5 kg of material was removed from the sample vessel for use in a radioelement assay of cuttings that had not been washed. Since the chalk and the clay cuttings consisted of fine and sticky particles, it was necessary to bring these into suspension before spraying. This was done by adding one litre of water to the sample vessel and stirring until the material formed a uniform grease. The spray rate used was 0.5 litre of water per minute. Sample 1 (chalk) and sample 2 (clay) were washed rather thoroughly, while the larger sample 3 was utilized to study the effect of the washing time by flushing samples 3A, 3B, and 3C with increasing quantities of water. Particles not retained by the bottom sieve were collected in large vessels where they were allowed to settle in the wash water for several days. The resulting fine fractions were retrieved by decanting.

The coarse, medium, and fine particle fractions collected after a completed wash-out operation were placed in metal trays and heated until dryness at 105°C. The resulting more or less sintered materials were powdered in a mortar or a ball-mill. An identical procedure was used to dry and grind the unwashed cuttings represented by the original sample material. Percentages of coarse, medium and fine particles determined by weighing the wash-out powders are presented in Table 4 which also shows the water consumption per unit mass of sample in each wash-out operation.

Table 4. Water consumption and associated particle fractions in the wash-out experiment

Cutting sample	Wash water per unit mass of sample (l/kg)	Weigh percent particles retrieved		
		Coarse (>2.4 mm)	Medium (0.18-2.4 mm)	Fine (<0.18 mm)
1 (chalk)	3.0	0.6	4.0	95.4
2 (clay)	3.9	1.4	23.8	74.8
3A (coarse clastics)	0.4	76.1	6.8	17.1
3B (coarse clastics)	1.5	35.3	29.0	35.7
3C (coarse clastics)	5.4	8.0	39.0	53.0

The small amount of material in the coarse-particle fractions for sample 1 and 2 made it necessary to utilize a supplementary radioelement assay method that requires much less material than the 200 to 300 grams needed to perform an assay with the laboratory gamma-ray spectrometer. The auxiliary method introduced at this stage of the investigation was that of neutron activation followed by the counting of delayed fission neutrons. This method provides the concentration of chemical uranium (in units of ppm U) in powder samples typically weighing from one to a few grams. The neutron equipment, which is installed at Risø's research reactor DR-3, was described by Kunzendorf et al. (1980).

3.1.2. Results

Table 5 shows the radioelement concentrations analysed in the unwashed, but dried and powdered portions of sample material. The assay results for the powder fractions from the wash-out experiment are presented in Table 6.

To extract meaningful information from these analytical data, it is appropriate to separately discuss the results for the chalk (sample 1), the clay (sample 2), and the Paleozoic cuttings (samples 3A, 3B, and 3C).

Sample 1. - According to the composite log for the well, the chalk section (221 to 440 metres) was formed by soft and very light-grey chalk plus calcarenite with a content of shell fragments and microfossils. The amounts of chert, shale, and sand were trace. More than 95% of the sample material was collected as fine particles whose thorium and potassium concentrations are in good agreement with those determined for the unwashed part of the sample. The conflicting eU assay values may reflect an uneven distribution of radon within the sample cans.

Table 5. Radioelement concentrations of unwashed, but dried and powdered cutting samples.

Cutting sample	ppm U	ppm eU	ppm Th	%K
1	0.59±0.03	0.58±0.04	0.85±0.11	0.17±0.02
2	2.94±0.08	2.44±0.06	9.75±0.15	1.63±0.02
3A	1.02±0.02	1.99±0.14	2.38±0.16	1.54±0.03
3B	1.03±0.09	0.67±0.05	2.54±0.13	1.46±0.02
3C	1.10±0.08	1.18±0.06	2.64±0.15	1.55±0.03

Table 6. Radioelement concentrations in the coarse (c), medium (m), and fine (f) particle fractions from the wash-out experiment.

Cutting sample	Fraction	ppm U	ppm eU	ppm Th	%K
	c	0.91±0.03	-	-	-
1	m	0.56±0.05	1.01±0.05	0.51±0.13	0.28±0.02
	f	0.64±0.04	0.87±0.04	0.89±0.10	0.15±0.02
	c	6.49±0.08	-	-	-
2	m	1.60±0.08	1.30±0.08	4.49±0.12	0.77±0.02
	f	3.51±0.04	3.17±0.08	11.77±0.21	2.04±0.03
	c	1.03±0.07	1.52±0.09	2.50±0.13	1.50±0.03
3A	m	1.06±0.16	1.96±0.13	2.30±0.14	1.59±0.03
	f	1.18±0.06	2.80±0.34	2.84±0.43	1.62±0.04
	c	1.06±0.06	0.72±0.05	2.48±0.13	1.32±0.02
3B	m	1.23±0.06	0.72±0.05	2.28±0.13	1.71±0.03
	f	1.16±0.03	0.95±0.05	3.77±0.12	1.33±0.02
	c	1.00±0.02	1.03±0.06	1.61±0.16	1.27±0.03
3C	m	1.09±0.15	0.99±0.05	1.67±0.14	1.98±0.03
	f	1.43±0.09	1.98±0.15	4.47±0.33	1.57±0.03

The agreement obtained for the Th and K concentrations relates to the fact that the chalk section was drilled with a fresh-water gel, i.e. there was no salt in the drilling mud to depress the radioelement concentrations shown by an unwashed cutting sample. However, the gel was based on 50 grams/liter of Wyoming Bentonite measured to contain 13 ppm U and 31 ppm Th. The analysed concentrations of about 0.6 ppm U and 0.9 ppm Th for the chalk may, therefore, partially have been contributed by bentonite particles. Two mud samples, collected at drilling depths of 130 and 393 metres, were found to contain 6 ppm U and 3 ppm U per dry weight of mud.

Sample 2. - The composite clay sample, originating from depths where a saltwater-polymer was circulated, contained 75% fine particles which must be assumed to have been clay particles mainly. Thus, according to Table 6, result 2f, the clay particles as such can be ascribed a thorium concentraion of about 11.8 ppm Th. Table 5, on the other hand, shows that the unwashed clay contained 9.8 ppm Th only. This discrepancy is largely an effect of the high fraction (approx. 25%) of medium-sized particles with a thorium content of 4.5 ppm Th. In fact, since 0.25 x 4.5 ppm Th + (1-0.25) x 11.8 ppm Th = 10.0 ppm Th, the content of 9.8 ppm Th in the bulk clay sample is almost completely explained by the diluting effect of the medium-sized particles. The composition is expected to be mainly quartz and feldspars in the silt and sand fractions.

Sample 3. - The Paleozoic coarse clastic rocks represented by this sample was drilled using a saltwater polymer of high salinity (14 grams of NaCl per litre). In the wash-out of sub-samples 3A, 3B, and 3C, performed with an increasing quantity of water per kg of sample material, more and more salt was flushed away with the washwater. At the same time an increasing percent of fine particles, presumably mud solids, was retrieved from the washwater (Table 4).

The percent of salt and other mud solubles washed out from each sub-sample can be estimated as

$$P = 100\ (x'/x - 1), \qquad (3.1)$$

where x' is the concentration of a radioelement in washed sample material, while x is the concentration of the same radioelement in the original, unwashed material. The concentration x' is here calculated by multiplying the radioelement concentrations determined for the wash-out powder fractions by the weight abundances of these and adding. Table 7 shows the result of such a calculation applied to the two most reliable indicator radioelements, uranium (in ppm U) and thorium. These data suggest a wash-out efficiency of approx. 30%, 70%, and 100% in the flushing of the three sub-samples (assuming that all the mud solubles had been removed from sample 3C).

Table 7. Ratios between the radioelement concentrations of washed out and unwashed cutting samples, and the resulting percentages of mud solubles contained in the latter.

Cutting sample	Washed - to unwashed concentration ratio U	Th	Suggested weight percent mud solubles removed from the sample material
3A	1.04	1.07	6
3B	1.11	1.13	12
3C	1.15	1.19	17

From Table 6 it can be seen that the fine particle fraction of sample 3C contained substantially more thorium and uranium than the coarse and medium particle fractions. This indicates that the fine particles were mud solids. In fact, dried mud samples representing the drilling fluid over the depth interval from 1440 to 1725 metres consistently showed a uranium concentration of 1.4 ppm U, which agrees well with the 1.2 to 1.4 ppm U found in the fine particles of samples 3A, 3B, and 3C.

The concentrations of approx. 1.1 ppm U, 1.7 ppm Th, and 2.0% K in the medium particle fraction of sub-sample 3C are probably the best estimate of the radioelement concentrations that are present in the cuttings of sample 3. These assay values contrast those of 1.0 to 1.1 ppm U, 2.4 to 2.6 ppm Th, and 1.5 to 1.6% K in the unwashed sample 3. This is an example where the result of analysing a bulk cutting sample is affected by two oppositely directed error sources: Mud solubles (mainly salt) which produce underestimated radioelement concentrations due to their dilution effect, and mud solids (presumably clay particles) which introduce an extraneous quantity of radioelement concentration. In the present example the thorium content of the mud solids overshadowed the diluting action of the mud solids, while the uranium present in the drilling mud happened to counterbalance the loss of uranium concentration caused by the liquid mud component.

3.1.3. General conclusions

Although the laboratory wash-out experiment was performed with only three large cutting samples, the experiment proved the existence of three potential sources of error in using bulk drill cuttings to assign radioelement concentrations to formations penetrated by the drill: Mud solubles, mud solids, and geochemically irrelevant material such as fall-down particles. Any of these normally occurring sample components may either enhance or reduce the concentration shown by a radioelement in the mixture of solids and liquids represented by a bulk cutting sample. The net effect depends on the abundance and radioelement content of each (disturbing) sample component. The wash-out experiment provided one example where the apparent thorium concentration of clay cuttings was reduced by almost 20% due to a rather high fraction of minor particles that contained 2 1/2 times less thorium than that carried by the clay particles. In another example the thorium content of hard-rock cuttings was overestimated by 50% because of the thorium contained in the mud solids.

3.2 Comparison with gamma-ray wireline logging

Returning tc the five wells which supplied a large number of consecutive bulk-cutting analyses, tapes with geophysical wireline logs were available for Farsø-1, Thisted-2, Tønder-4 and Tønder-5. The gamma-ray logs of these four wells were logs of the total downhole gamma-ray intensity with this intensity expressed in gamma API units. A gamma API unit refers to the radiation intensity measured in a calibration pit established at the University of Houston in 1959 by the American Petroleum Institute. The center zone of the pit defines a logging signal of 200 API units, which is about twice the signal recorded with an average shale (Johnstone, 1964). The readings were spaced at intervals of either 10 cm or 15 cm (1/2 ft.), i.e. they provided a much better spatial resolution than that obtained by taking a bulk cutting sample at 5-meter intervals. To investigate the degree of matching between the logs and the radioelement assay values, it was consequently necessary to smooth the logs. This was done using a symmetrical filter whose factors were the binomial coefficients

$$P(n,m) = \frac{n!}{(n-m)!\,m!}\,, \qquad (3.2)$$

where n is even, and where m varies from 0 to n. The number of points, n, included in the filter was chosen so as to produce a filter function with an FWHM (full width at half maximum) of five metres.

Each filtered gamma-ray log provided a series of observations which were regarded as samples of a dependant variable, y. The expectation value of the latter, $\bar{y}$, in each 5-meter borehole interval covered by a cutting analysis, was represented by the equation

$$\bar{y} = a_U x_U + a_T x_T + a_K x_K, \qquad (3.3)$$

where x_U, x_T, and x_K are the concentrations of uranium, thorium, and potassium analysed in the sample. The factors a_U, a_T, and a_K are here unknown "calibration" constants for the particular tool used to record the gamma-ray log. The use of linear regression of (x_U, x_T, x_K) on y furnished the values of a_U, a_T, and a_K. It was then possible to calculate $\bar{y}$ in the points where a data set (x_U, x_T, x_K, y) was available.

Figures 5 to 8 show the result of performing this combined data smoothing and regression analysis. The solid curve on each figure is the smoothed, experimental gamma-ray log, $\bar{y}$, while the dashed curve is the corresponding expected log, $\bar{\bar{y}}$. To obtain a direct impression of the agreement between y and $\bar{\bar{y}}$, the deviation log $y-\bar{\bar{y}}$ is also displayed (using a dot-and-dash signature).

In using the deviation logs to measure the consistency of the geochemical data and logging data, it should be born in mind that the two kinds of data represent two different types of sampling. The radioelement assay values are the concentrations of U (in ppm eU), Th, and K in a mixture of cuttings obtained by drilling for a length of roughly five metres. The smoothed logging data, on the other hand, are total gamma-ray signals that originate mainly from the formations penetrated by the drill. It is quite obvious that any sharp transition in the radioelement concentration versus the depth cannot be as well reflected in the assay data as it will be in the wireline log, despite the smoothing applied to the latter. Some of the details shown by the wireline logs are therefore lost in the corresponding geochemical logs. Another source of discrepancy is the higher susceptibility of the geochemical data to radioelements present in the drilling mud. This effect is particularly clearly seen in the chalk section of Farsø-1 (50-1430 m) and in the 50 metres thick layer of rock salt at approx. 1600 m in Tønder-4. The radioelement contents suggested by the wireline logs are here significantly smaller than those analysed in the bulk cutting samples. As a matter of fact, Farsø-1 and Tønder-4 are the two wells that produced the least degree of matching between wireline logging and geochemical sampling. The

matching provided by Tønder-5, and - especially - Thisted-2 is considerably better. The mud logs for the wells did not substantiate why logging and sample analysis in some instances produce an essentially congruent picture of the radioelement distribution down through a borehole, while in other instances the two kinds of data are poorly correlated or even conflicting.

3.3. Summary

The evidence presented up to now shows that the radioelement concentrations measured in bulk cutting samples must be used with great caution. In the first place the impure nature of the sample material makes it difficult to be very specific about the geochemical meaning of the assay values and the radioelement abundance ratios they provide. Secondly, the sometimes contradictory radioelement levels postulated by sample analysis on the one side and wireline logging on the other indicate that a geochemical Th-U-K log may be different from the Th-U-K log provided by a spectral wireline tool, especially over the sections of a borehole which intersects rock of low radioelement abundances. The figures presented in the preceding subsection suggest that the result of analysing bulk cutting samples is of doubtful value over the following depth intervals: Farsø-1, 50 to 1430 m; Tønder-4, 1250 to 1650 m; and Tønder-5, 1650 to 1700 m.

4. EVALUATION OF THE RADIOELEMENT-CONCENTRATION DEPTH PROFILES

The washout experiment and the comparison between cutting analysis and downhole gamma-ray logging showed that it may be problematic to accept the radioelement concentrations shown by bulk cutting samples. We decided, however, to interpret the sealed-can assay values in terms of characteristic radioelement concentrations for the formations intersected by the wells. In broad terms, the interpretation described in this chapter is performed against lithology, facies, and sedimentary depositional environment, disregarding the disturbing effects caused by mud solids, mud chemicals, and fall-down particles contained in the cutting samples.

Except for the Thisted-2 well, only few and scattered mineralogical data were available. The direct correlation between geochemistry and mineral distribution is therefore limited. The results are described well by well for the lithostratigraphical units from TD (total depth) and up-hole. All depths are in metres below Kelly Bushing (KB).

A summary of the assay results divided in accordance with the lithostratigraphy is included in the Appendix.

4.1. Thisted-2

The interval analysed (3285 m-1305 m) encompass the Skagerrak Formation (3285 m-1598 m), the Oddesund Formation (1598 m-1356 m) and the Vinding Formation (1356 m-1305 m). The total GAPI curves (Figure 6) from cutting analysis and from wireline log correlate well which indicates that the cutting analyses are not hampered by "fall-down" materials from higher levels in the hole. The radioelement distribution from the analyses of bulk cuttings is shown in Figure 9 and the ratios Th/U, Th/K and U/K are shown in Figure 10.

4.1.1. Skagerrak Formation

The formation is predominantly a sandstone sequence with a thickness of more than 1687 m (3285-1598 m). It consists of interbedded claystone and siltstone layers, particularly in the upper part. The sediments are red beds which were deposited in braided channels and as flash floods in a desert environment.

The general petrography and diagenetic processes have been studied in drill cores and side wall cores and the results are reported by Nielsen (1982, 1, 2) and Jensen (1985). The sandstones are classified as arkoses, subarkoses and lithic arenites. The lithic fragments in the sandstone include varying proportions of plutonic granitic rocks, sedimentary rocks and volcanic rocks.

The claystone intervals are occasionally associated with caliche and may be of pedologic origin.

Diagenetic processes have altered the immature Skagerrak Formation sandstones considerably. The deepest part is characterised by precipitation of illite and graywakefication (clay replacement) of the siliciclasts. An intermediate zone shows an extensive dissolution of feldspar whereas the shallowest part of the formation still bears evidence of neoformation of a series of minerals, e.g. quartz, feldspar, carbonates, and anhydrite.

The variations shown by the gamma-ray wireline log are accompanied by radioelement variations which match the lithology and geological processes (Figures 6 and 9). The K-content varies between 2,5% and 5% with an average close to 4%. The high K-contents primarily reflect the variations in the amount of K-feldspar which may exceed 20% by volume around 2200 m (Jensen, 1985). The marked decrease in K from 2400 m to 2700 m coincides with diagenetic dissolution of the K-feldspar.

The amount of mica is generally below 1%, and K-feldspar and illite are the only K-bearing minerals of importance. The stabilisation of the K-content around 3% below 2750 m to TD is explained by the crystallization of diagenetic illite in this interval. The

increase in K from the top of the formation (1598 m) to 2250 m most probably reflects the amount of K-feldspar in the primary clastic minerals modified by early diagenetic overgrowth and the occurrence of infiltration by clay minerals with depth.

The U-content varies between 2 ppm and 5 ppm which is above the average range for sandstone. Except for a minor decrease from 2360 m to 2900 m there is no systematic variation in the U-content. The general high U-level is most probably due to the granitic composition of a large proportion of the lithic fragments and to the terrestrial depositional regime. EDX (energy dispersive x-ray fluorescence analysis) was carried out on 22 core samples in the interval 2750-3200 m (Kunzendorf and Gwodz, 1982). The samples were analysed for Ca, Ti, Mn, Fe, Cu, Zn, Rb, Sr, Y and Zr. A correlation coefficient matrix which includes the radioelement cutting analyses is presented in Table 8. It is seen that U does only show a minor correlation with Ti. This indicates that Uranium was never mobilized in the chemical environment governing this part of the Skagerrak Formation.

Table 8. Correlation coefficients for selected elements in drill core samples in Thisted-2. The matrix is based on 22 samples analysed by energy dispersive x-ray and gamma-ray spectrometry (from Kunzendorf and Gwodz, 1982).

	Ti	Mn	Fe	Cu	Zn	K	U	Th	Rb	Sr	Y	Zr	NB
Ca	-.320	0.715	-.044	0.029	0.227	-.726	-.347	-.385	-.721	0.602	-.304	-.467	-.496
Ti		-.129	0.201	-.113	-.173	0.278	0.367	0.534	0.285	-.280	0.294	0.629	0.449
Mn			0.396	0.066	0.079	-.259	-.076	-.083	-.400	0.117	0.200	-.199	0.032
Fe				0.298	0.220	0.201	0.159	0.336	0.065	-.137	0.597	0.200	0.495
Cu					0.794	0.216	0.123	-.107	-.007	0.323	0.317	-.110	0.174
Zn						-.141	0.051	-.144	-.260	0.598	0.045	-.257	-.082
K							0.352	0.405	0.634	-.570	0.552	0.497	0.642
U								0.546	0.364	-.224	0.403	0.397	0.399
Th									0.351	-.307	0.355	0.657	0.449
Rb										-.469	0.275	0.362	0.493
Sr											-.262	-.339	-.415
Y												0.548	0.772
Zr													0.683

A remarkable U-anomaly of 17 ppm is found at 2220-2230 m. This radioactive concentration responds with an amplitude peak of 290 API units on the gamma-ray wireline log (Figure 6). The anomaly cannot readily be explained, but as it correlates with a marked increase in Th, it most probably reflects a concentration of radioactive refractory heavy minerals. Due to the nature of the depositional environment the anomaly is not expected to have significant lateral continuity.

The Th-content is high (10-13 ppm) from the top of the formation (1598 m) down to 2400 m. From this level the Th-content decreases to a minimum of 5 ppm at 2950 m. Below 2950 m there is a steady increase to approximately 10 ppm Th at TD (3285 m). The distribution of the thorium matches the variation in the clay mineral content. From 1598 m to 2400 m the formation has a considerable number of clay bed intercalations. The decrease in Th from 2400 m to 2950 m is coincident with a variation in the amount of clay in this interval. The petrographic study by Jensen (1985) shows that illite (which is generally very low in Th) occurs below 2750 m and that authigenic kaolinite (which is generally high in Th) is formed below 3150 m. The Th distribution curve is in agreement with these observations. The correlation coefficient matrix in Table 8 shows that Th has a positive correlation with Ti, K and U in the cored interval 2750 m-3200 m. Obviously a considerable part of the thorium within the relatively clay poor zone may be contained in Ti and U bearing refractory minerals.

4.1.2. Oddesund Formation

The Oddesund Formation has a thickness of 242 m (1598-1356 m) and consists of a series of anhydritic and calcareous claystones with occasional minor sandstone intervals. The formation has been divided into three members 01, 02 and 03 (Bertelsen, 1980) of which the middle member 02 contains evaporite beds. The Thisted-2 well is located marginally in the Oddesund depositional basin and the evaporite beds are restricted to the presence of anhydrite beds of 1-4 m in thickness interbedded with the claystone.

The average K, U and Th contents are 2.2%, 2.6 ppm and 8.0 ppm respectively. These values are within the ranges for common shales (Table 2). There is a general increase in the K-content with depth, whereas U decreases slightly with increasing depth. Minimum values for all three elements can be attributed to anhydrite rich intervals.

A marked relative enrichment of uranium to 3.5-5 ppm is seen in the top of the 03 member (1385-1360 m) and in the 02 member at 1550 m. The anomalous zones may be due to marine incursions causing a slight enrichment in organic matter and associated uranium.

4.1.3. Vinding Formation

The Vinding Formation has a thickness of 51 m (1356-1305 m) and consists of calcareous claystone with minor limestone intercalations. The sediments were deposited in a brackish shallow marine environment (Bertelsen, 1978). The radioelement content in the four analysed samples decreases with depth, which reflects the increasing amount of carbonate relative to clay minerals. The relative high U, Th, K contents in the top of the formation are in agreement with the analytical results from the Farsø-1 well which penetrated the upper ten metres of the Vinding Formation.

4.2. Farsø-1

The formations intersected in the Farsø-1 well form a stratigraphic continuation of the analysed Triassic interval in the Thisted-2 well. The Farsø-1 well is located approximately 40 km to the east of the Thisted-2 well. The well has a depth of 2952 m, and encompasses the following lithostratigraphical units:

Gassum Formation (2941-2743 m), Fjerritslev Formation (2743-1978 m), Haldager Formation (1978-1925 m), Bream Formation (1925-1714 m), Vedsted Formation (1714-1490 m), Rødby Formation (1490-1435 m), Maastrictian and Danian chalk units (1435-surface). A total of 203 samples have been analysed with an average sample interval of 6 m from 2949 m to 1435 m and 90 m intervals in the overlying

chalk section. The experimental and calculated gamma-ray logs from wireline logging and cutting analysis (Figure 5) show an overall agreement from the base of the chalk to TD. However, the curves, do not match each other in detail to the extent seen in the Thisted-2 well. Generally the Farsø samples seem to be more contaminated by fall down and mud constituents than are the Thisted samples. In the chalk section the GAPI-logging values estimated from the cutting analysis are 4-12 API units higher than the filtered gamma-ray wireline log. The deviation is a "null effect" arising from the uncertainty of the regression slope for the line that correlates experimental and theoretical logging values in the deeper, more radioactive part of the well. The radioelement distribution from the analyses of bulk cuttings is shown in Figure 11, and the ratios Th/U, Th/K and U/K are shown in Figure 12.

4.2.1. Gassum Formation

The Gassum Formation is a fluvio-deltaic deposit consisting of upward coarsening sequences of mainly arenaceous sediments (Bertelsen, 1978). In the Farsø-1 well the formation is divided into four members G1-G4. The G2 member is composed of carbonaceous claystones and minor siltstone layers. The G1 and G3 members have equal proportions of sandstone and silty claystone and the G4 member is mainly sandstone with minor silt and clay intercalations in the lower part.

The sandstones are at present in a chemically reduced state throughout formation. Coal, lignite and micro-lignite is common i G4, and glauconite occurs occasionally.

The thicknesses of the individual beds are insufficient to be reflected in the lithological log and the radioelement abundance logs. Average radioelement contents are calculated on the basis of 18 sample analyses. The following results are significant for the mineralogical composition of the clastic rock suite:

K	0.9- 2.6 %	av. 1.7 %
U	2.2- 3.8 ppm	av. 3.1 ppm
Th	7.1-12.9 ppm	av. 10.0 ppm

There is a general increase in U with depth whereas the K and Th contents show an overall but less distinct distribution trends (Figure 12).

The Gassum sandstones are classified as arkoses and subarkoses. In addition to the feldspatic component the sandstones typically contain 3-12% (vol) authigenic clay minerals (Priisholm et al., 1986). Within the total clay volume kaolinite constitute 50-70% and illite chlorite and mixed layer clays 30-50%.

The relative amount of clay in the formation contributes to the control of the Th-distribution.

The distribution of U is explained by absorption of U partly on clays and partly on fine organic matter in the detrital clay layers deposited in a near shore reducing environment.

The amount and distribution of K is controlled by the arkosic composition of the sandstone and by the distribution of clays other than kaolinite e.g. illite.

4.2.2. Fjerritslev Formation

The Lower Jurassic Fjerritslev Formation has a thickness of 765 m (2743-1978 m) in the Farsø-1 well. It is a series of marine claystones with minor silt or sandstone intercalations. The formation is calcareous throughout the interval. It is subdivided into four members FI-FIV (Michelsen, 1978). The radiometric data have been grouped and processed with correspondence to the four-fold division which lithologically are rather uniform. The source rock potential of the Fjerritslev Formation members varies and it has been extensively. The mineralogy and organic content are well documented (Sedico, 1984 I, II, Østfeldt, 1986 I,II; Clausen 1987).

The radioelement contents, however, vary only slightly with depth and it is not possible to distinguish between the individual members on the basis of their U, Th, K contents. The elemental concentrations are typical of common shales (Table 2). The geochemi-

cal variation is controlled by the clay mineralogy (K) and the availability of U and K for absorption on these clays. The clay minerals are mainly kaolinite and illite with minor quantities of chlorite, glauconite and smectite. The kaolinite/illite ratio is approximately 2. The clay controlled radioelement distribution is demonstrated by the Th/U ratio curve with ratios of 6-7 for the clean claystone intervals and 3-5 for the silty and sandy intervals. The U-distribution curve may also be influenced by the haphazard occurrence of microlignite with associated uranium.

4.2.3. Haldager Formation

The Middle Jurassic Haldager Formation has a thickness of 53 m (1978-1925 m). It is divided into two members, the Haldager Sand overlain by the Flyvbjerg Member (Michelsen, 1978). The petrography of the Haldager sand is presented by Nielsen & Friis (1984) and Priisholm et al. (1986). The Haldager Sand has a fairly simple mineralogical composition, being quartz arenites with kaolinite and quartz as the predominant authigenic constituents.

Since only six samples were available the general radioelement geochemistry will be discussed in the subsection on the Aars-1 well.

4.2.4. Bream Formation

The Upper Jurassic Bream Formation has a thickness of 211 m (1925-1714 m) in the Farsø-1 well. Michelsen (1978) subdivided it into a lower claystone unit, the Børglum Member, and an upper silty and sandy claystone unit, the Frederikshavn Member. The depocenter of the Bream Formation is approximately 100 km to the north of Farsø-1 where the formation has a thickness of more than 250 m. Both members are marine deposits, the Frederikshavn Member representing a more near-shore environment with coarse clastic intercalations.

The lithological differences between the two members are reflected in the average radioelement contents

	K%	U ppm	Th ppm
Frederikshavn Mb.	1.7	2.4	9.0
Børglum Mb.	2.3	3.2	11.1.

The U, Th, K ratios are relatively constant throughout the Bream Fm. (Figure 12) which suggests that radioactive minerals in the two members are identical and occur in equal proportions.

The Børglum Member has on the average more K and U than have other marine claystones within the Jurassic section. This results in Th/U and Th/K ratios which are significantly different from the Fjerritslev and Vedsted Formation values and which are expected to be regional geochemical signatures.

4.2.5. Vedsted Formation and Rødby Formation

The Lower Cretaceous Vedsted Formation has a thickness of 224 m (1714-1490 m). Except for a moderate carbonate content there are no marked lithological changes from the underlying Bream Formation. The Vedsted Formation contains marine claystones with intercalations of silt and sand, particularly in the central part of the formation. The Rødby Formation has a thickness of 55 m. It is a calcareous claystone which overlies the Vedsted Formation claystone conformably. There is, however, a strong radiometric contrast between the claystone lithology in the two formations.

The average analytical results are as follows:

	No. of samples	U (ppm)	Th (ppm)	K (%)
Rødby Fm.	7	2.0	7.8	1.9
Vedsted Fm.	20	2.8	10.5	1.8

The shift in U and Th concentration may be useful in the definition of the boundary between the Vedsted and the Rødby Formations. This boundary is less distinct from the total gamma and other wireline log pattern.

Fluctuations in U, Th and K contents are observed in the Vedsted Formation. A peak in U (5,3 ppm) at 1575 m is accompanied by troughs in Th and K (8,0 ppm and 1,3%). The available lithological logs are not sufficiently detailed to explain the observed anomalies.

4.2.6. Chalk group

The Chalk Group, which has a thickness of 1435 m in the Farsø-1 well, has been analysed with sample intervals from 5 m to 90 m. A total of 21 samples were included, providing average concentrations of 0.2% K, 0.6 ppm U and 1.5 ppm Th.

The Chalk Group has informally been divided into 6 units (Lieberkind et al. 1982). As the subdivision a.o. is reflecting the variations in clastic material the boundaries may be in agreement with changes in the inorganic geochemistry.

The results of the cutting analyses, although close to the detection limit, make it possible to discriminate between several of the chalk units (Figure 12). The base of unit 2, the Turonian shale, appears with a strong positive Th/U anomaly and negative Th/K and U/K anomalies. Unit 2 is distinguished from unit 3 and 4 by a higher Th/U ratio. Unit 5 has a still lower Th/U ratio (ca. 1), and zones with a relative enrichment of Th and U are characteristic. The trace element geochemistry of the boundary zone between unit 5 and 6 (Maastrichtian and Danian chalk) have been studied by Jørgensen (1986) and by Kunzendorf et al. (1986) on samples from the North Sea. The relatively high and uniform clay content (15-20%) of the Unit-6 chalk gives a clear definition of the formation boundary by the U/Al ratio being comparatively low in the Danian chalk.

4.3. Aars-1

The Aars-1 well is situated approximately 15 km east of Farsø-1. The two wells largely intersect the same stratigraphic interval and they both represent the central part of the Danish subbasin. As such they are expected to be geochemically associated in terms of geochemical control from the depositional regime.

The radioelement distribution and the element ratios are presented in Figures 13 and 14. A comparison with the analytical data from Aars-1 and Farsø-1 shows a number of similarities as well as discrepancies.

The U and Th contents and relative variation with depth are almost identical in Aars-1 and Farsø-1. The overall trend is a steadily decreasing Th concentration in the marine claystone as the deposits become younger. Conversely the U-concentration increases slightly from the base of the Fjerritslev Formation to the Vedsted Formation. The oppositely directed trends result in a strong gradient on the Th/U ratio.

The cutting analyses show similar depth-related distribution patterns for K in Aars-1 and Farsø-1. These are tied to fluctuations in the amount and composition of the clay minerals. However, there is a systematic difference of approximately 1.5% K between the two wells, Aars-1 having the highest concentration. It is unlikely that the difference is due to a lithological compositional difference. In consideration with the correspondence of U and Th, the difference in the K-values is possibly explained by a potassium contamination from the drilling mud in Aars-1.

4.4. Tønder-4 and Tønder-5

The distance between Tønder-4 and Tønder-5 is 5 km. Both wells were sampled and assayed from TD to the surface with a sample interval of 5 metres except for the chalk sections which have been assayed with a sample interval of 20 metres (Tønder-4) and 30 metres (Tønder-5). There is an overall good correlation between the two wells. For this reason only the Tønder-4 has been selected for the detailed data presentation below. Any significant deviation between Tønder-4 and Tønder-5 is described in the text. The radioelement distribution logs and the radioelement ratio logs for the two wells are presented in Figure 15 to 18.

The interval analysed in Tønder-4 (1870 m - 90 m) encompasses the following formations. Bunter Shale Formation (1870 m - 1827 m), Bunter Sandstone Formation (1827 m - 1622 m), Ørslev Formation (1622 m - 1440 m), Falster Formation (1440 m - 1267 m), Tønder Formation (1267 m - 1081 m), Oddesund Formation (1081 m - 957 m), Vedsted and Rødby Formations (957 m - 900 m), Chalk group (900 m - 425 m), Tertiary/Quaternary clay and sand (425 m - surface).

4.4.1. Bunter Sandstone Formation

The formation is informally divided into a Lower Bunter Sand unit (1827 m - 1792 m), and an Upper Bunter Sand unit (1691 m - 1622 m) separated by a 101 m thick claystone/siltstone unit. The Lower Bunter sand is predominantly porous aeolian sandstones, whereas the Upper Bunter sand is a more complex series of fluvial deposits. The interbedded claystones and siltstones represent sabkha and inland basin facies. The sediments were deposited in a warm and arid climate. They are redbeds with a high proportion of evaporite minerals (Clemmensen, 1985).

Average radioelement concentration were calculated separately for Lower Bunter sand and for the mixed sandstone, siltstone and claystone lithology above. The aeolian sand is markedly lower in both U, Th and K than is the impure fluvial sand and basin claystones (Figure 15). The claystone/siltstone interval (1792 m - 1691 m) has a significant high uranium content of 3-4 ppm compared with the Upper Triassic claystone sequences in the well. It is suggested to be an evidence for the subaeric deposition of the claystone with an absorption of uranium on the ferrihydroxides/oxides. The contrast between uranium in the sabkha clays and in claystones of the overlying fluvial regime is particularly well seen in Tønder-5 (Figure 17). A negative anomaly at 1680 m-1690 m in U, Th and K is coincident with a strong cementation of the sandstone with anhydrite and halite. Petrographic analyses do not indicate major compositional differences in the clastic mineral assemblage between the cemented and uncemented zones. The depletion may be associated with dissolution of complex silicates in hypersaline brines which flushed the sandstone when nitrogen entered the top of the structure (Laier and Nielsen, 1987).

4.4.2. Ørslev Formation

The Ørslev Formation (1613 m - 1440 m) may be divided into the lower evaporites (Röt Salt) and overlying claystone redbeds. The lithological sequence and its U, Th, K geochemical signature reflect the paleogeographical changes in the coastal sabkhas where the sediments were deposited. The variations in the U, Th, K contents are more significant than is the variation in the sabkha claystone lithology. The U, Th and K concentrations vary conformably (Figures 15, 17), which may indicate a proportional high mud solids component in the analyzed samples.

It is suggested that the highs in general represent the basin marginal facies and the lows the central marine evaporite facies of the basin. Within the Röt salt minor clay bearing intervals stand out as small positive anomalies.

4.4.3. Falster Formation

The Falster Formation (1440 m - 1267 m) is composed of mainly calcareous or dolomitic claystone with interbedded horizons of limestone and dolomite. The claystone and limestone was deposited in a shallow marine or brackish sea and the sediments are generally in a reduced state.

The U and Th contents are fairly constant around 2 ppm and 5 ppm throughout the formation. A minor U anomaly of 3-4 ppm is seen 40 m below the top of the formation both in Tønder-4 and Tønder-5. The anomalies are associated with limestone layers. It may be a facies controlled enrichment in the carbonates and thus the anomaly may have significance as a geochemical stratigraphical marker.

Particularly in Tønder-4 the K content increases gradually from approx. 1.5% to 2.5% in the upper 50-80 m of the formation. The increase is obviously accompanied by a relative increase in clay/carbonate mineral ratio.

4.4.4. Tønder Formation

The Tønder Formation (1267 m - 1081 m) consists of slightly dolomitic claystones with varying state of oxidation as shown by the red and grey colours. In the upper half of the formation the claystone is interbedded with sandstone horizons occasionally exceeding 10 m in thickness.

Bertelsen (1980) suggests that the claystones were deposited on a coastal plain under shifting subaerial and marine conditions. The sand intercalations are considered to be fluvial deposits on the coastal plain.

The change from the marine environment in the Falster Formation is a.o. shown by a strong increase in the concentrations of all three elements (Figures 15, 17). The K content exceeds 3% in the sections dominated by clay minerals only. The U and Th concentration follow changes in the K content and as such these elements are absorbed on the clay minerals. Around 1250 m in Tønder-5 the Th content exceeds 10 ppm. Frequent variations in U are possibly due to local changes in the redox potential.

4.4.5. Oddesund Formation

The Oddesund Formation (1081 m - 957 m) consists of red or brown claystones which may be slightly silty, calcareous and anhydritic. They are continental deposits which represent the marginal facies of a large evaporite basin extending to the south.

The lithological composition of the Oddesund Formation shows no significant variations from Tønder-4 and Tønder-5. On the contrary the radioelement concentrations show considerable variations although the major trends are uniform in the two wells. In the top of the formation a marked deficiency in K is accompanied by a Th enrichment. The resulting Th/K peak (Figures 16, 18) may be a useful lithological marker and in future work it should be investigated whether the geochemical anomaly can be stratigraphically related to the more detailed division elsewhere in the basin.

The Th/U and U/K ratios in Tønder-5 indicate a three-fold lithological division of the formation in the Tønder area. However, further petrographical and geochemical data are needed to eludicate this feature. The average U, Th, K concentration correspond closely to the data from Thisted-2 in the Danish Sub-basin (Figure 9).

4.4.6. Vedsted Formation and Rødby Formation

The Vedsted Formation (957 m - 905 m) is lithologically divided intc a basal sand section with a thickness of 20 m overlain by 33 m of marine clays. The top of the sand layer is rich in iron-oolites (siderite and geothite) and it is associated with a strong enrichment in Th (15-20 ppm).

On the average the U, Th, K contents in the Vedsted Formation clays are slightly richer in Th and slightly poorer in K compared with claystones in the Oddesund, Tønder and Bunter Sandstone formations. This characteristic feature is shown by Th/K values of 4-5 in the Vedsted claystones and Th/K values of 3-4 in the other formations (Figures 16, 18).

The number of data points from the Rødby Formation is too small for a reliable data evaluation.

4.4.7. Chalk group

The Chalk group has a thickness of 475 m (900 m - 425 m). Unlike Farsø-1 the group is not attempted divided in lithostratigraphical units, and the radioelement distribution is evaluated for the entire section. A total of 51 and 21 samples were analysed in Tønder-4 and Tønder-5 respectively and the average concentrations are listed below and compared with the data from Farsø-1.

	K%	U ppm	Th ppm
Tønder-4	0.6	1.1	2.6
Tønder-5	0.7	0.9	2.9
Farsø-1	0.2	0.6	1.5

The overall distribution pattern is controlled by the amounts of glauconite (K) and clay minerals (K, U, Th), and it is seen that the chalk unit at Tønder is impure compared with Farsø-1. The high Th-values are probably influenced by bentonite in the drilling mud.

There is a general increase in the U, Th, K contents towards the top of the chalk section. Stepwise changes are seen at 530 m b KB and the ratio-curves suggest the upper 105 m of the chalk to belong to a separate chalk unit. Similar unit boundaries may exist at 700 m, 780 m and 850 m. Like in Farsø the Turonian shale at the base of Chalk unit 2 appears as a Th/U peak and Th/K and U/K troughs. Apart from the Turonian shale there is no obvious correlation between the chalk units in Tønder-4 and Farsø-1.

The distribution pattern in Tønder-5 is similar to Tønder-4 except for the top 100 m where a drop is seen in both U, Th and K. It may indicate that the general erosion level in Tønder-4 is approx. 100 metres deeper than in Tønder-5. This is in agreement with the position of Tønder-4 being closer to the crest of the structure than is Tønder-5.

4.4.8. Tertiary and Quaternary

The Tertiary and Quaternary interval (425 m - surface) has not been lithostratigraphically subdivided and there are considerable compositional differences between Tønder-4 and Tønder-5. Similar variations are seen in the radioelement analyses and only a few observations may have geochemical significance in common for the two wells.

Around 270 m b.KB there is a distinct enrichment in Th relative to U and a minor enrichment in K relative to U (fig. 16). The boundary may coincide with the Eocene-Oligocene hiatus (Dinesen et. al., 1977). In support of this view is the existence of a strong combined U and K anomaly above the unconformity. The anomaly is suggested to represent the glauconite rich basal part of the Middle Oligocene, Branden Clay (Christensen and Ulleberg, 1973).

5. DISCUSSION

A total of 1329 gamma-ray analyses of K, U and Th from Cainozoic and the Mesozoic sedimentary rocks in the Danish Subbasin and the North German Basin provides a unique basis for a geochemical characterization of the analyzed sedimentary sequence.

The position of Thisted-2, Farsø-1 and Aars-1 in the Danish Subbasin represents broadly speaking the central part of the basin with predominantly distal depositional facies in relation to the source areas. It is therefore argued that a compilation of the geochemical data into a modelled lithostratigraphic profile may serve as a reference radioelement type profile for the Danish Subbasin. The reference profile is shown in Figure 19; it is constructed on the basis of the average radioelement values from the three wells. In applying the profile it must be kept in mind that geochemical characterisation of sediments changes laterally according to variations in depositional environment and lithological composition.

Lateral variations in the radioelement contents may be illustrated by the relationship of U and Th/U as shown in the cross plot in Figure 20. Broadly speaking, the relative variations in the U content is sensitive to the depositional environment, whereas the Th/U ratio is also indicative of the mineral assemblage and parent rock type, distance to source area and diagenetic alterations. Figure 20 is constructed on the basis of the analytical average values for the major lithostratigraphical units (Figure 2). It should be noted that the cross plot include data from both the Danish subbasin and the North German basin. The distribution pattern in the U-Th/U plot is developed into a depositional-compositional model as shown in Figure 21. This model may with caution be applied also outside the Danish area with respect to the relative positions of the lithofacies groups and their radioelement geochemistry.

Tønder-4 and Tønder-5 are situated in the northernmost part of the North German Basin flanking the main source areas to the north, the Ringkøbing-Fyn High. As the facies variations are expected to vary more rapidly along the basin margins the Tønder wells have not been used for the construction of a reference profile.

Provided that the geochemical characterization of the sediments on the average is of a general nature, i.e. the reference profile reflects general and correlatable variations, it is in principle possible to explain all deviations from the profile in terms of geochemical proccesses during geological time. These anomalies may a.o. be governed by local incongruencies in the water-rock interaction processes.

In subsection 1.2 it was stated that incongruent reactions ultimately might lead to an enrichment of incompatible elements at shallower levels in the sedimentary column. The radiometric reference profile does not confirm that this process has taken place on a megascopic scale. Beusen et al. (1986) has in the laboratory studied main element and trace element behaviour during rock-fluid interactions at 200° C. They show that thorium is preferentially enriched in the solid phase as this element is fixed by refractory impurities and accessory minerals. The present study confirms the general concept that Th is also easily absorped by clay minerals e.g. in the Fjerritslev Formation.

It may therefore be concluded that although Th is involved in incongruent leaching processes the element is not very mobile. Thorium is accordingly a stable geochemical element through geological time with other stable elements as a reference.

Petrographic examination of clastic sediments shows that potassium is involved in important geochemical diagenetic processes, for instance dissolution and precipitation of potassium feldspars and neoformation of K-bearing clay minerals such as illite. Chemical analysis of formation waters from Haldager and Gassum For-

mation sandstone in Farsø-1 and Thisted-2 shows K concentrations in the order of 1-2 g/l (T. Laier, personal communication). Although stoechiometric proportions between K and associated elements is not comparable in the natural system, it becomes evident that a large amount of K is transported in the water phase during burial compaction of the sediments. Laboratory experiments by Berger et al. (1986) show complex K-distribution at the solid-fluid boundaries. There is strong evidence that K is involved in incongruent reaction processes and that K in solution is subject to long distance transport in the sedimentary basin. The K-column in the reference profile is therefore the geochemical signature of the residual detrital mineral composition overprited by subsequent diagenetic alteration which is still in progress.

It was stated in subsection 1.2.1 that uranium is a highly mobile element particularly in the oxidized state. The data evaluation and the U-Th/U cross plot demonstrate the relative enrichment of uranium in the fine-grained redbed facies. The minerals hosting absorped uranium are predominantly minerals which are stable at the present temperature-pressure regime. Accordingly, only a minor fraction of the uranium is available for transport as a result of the diagenetic alterations. It is therefore argued that the distribution of U in the reference profile (Figure 19) is a stable geochemical feature which mainly developed during deposition and early alterations in the zone influenced by meteoric water.

6. CONCLUSIONS

A total of 1329 well cutting samples from the Danish Subbasin and the North German Basin were analysed for U, Th and K. A radiometric reference profile was constructed for the Mesozoic sequence in the Danish Subbasin, and a geochemical lithofacies model was suggested for common sedimentary regimes. The following conclusion are presented with respect to the observed geochemical distribution of U, Th and K in the Danish area.

1. Uranium was highly mobile during deposition but is presently of limited mobility as it is fixed by mainly stable mineral phases at depth. It provides information on the depositional environment, its oxidation state and its content of organic compounds.

2. Thorium has been very little mobile during the geological history. As such it may be applied as a stratigraphical marker. Its varying occurrence in stable mineral phases reflects characteristics and differences in the source areas for the sediments. Thorium which is released to the formation fluids is readily absorped by clay minerals.

3. Potassium occurs in several mineral phases which are unstable during changing physio-chemical conditions. Thus the distribution not only varies according to the original mineralogical composition but also according to the large scale pattern in dissolution and transport systems. Megatrends in the distribution within lithological units are related to both original mineral composition and to diagenetic processes.

Despite their contents of mud components and fall-down material, bulk drill cuttings seem to be representative of the allocated depths. Further, the variation in radioelement contents and ratios allowes an application of cuttings in regional geochemical

studies. The method seem useful particularly with respect to correlation of marine sequences. Additionally, provenance and lithofacies mapping of both marine and terrestrial sequences may be improved by inorganic geochemical studies. The method also provides a helpful tool in outlining major diagenetic alteration trends.

The successful performance of the K, U, Th survey on the basis of laboratory sealed-can gamma-ray analysis therefore suggests new fields of application for the natural spectrometric gamma-ray wireline log in lithofacies mapping, source area characteristics and diagenetic processes.

7. ACKNOWLEDGEMENT

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FIGURES

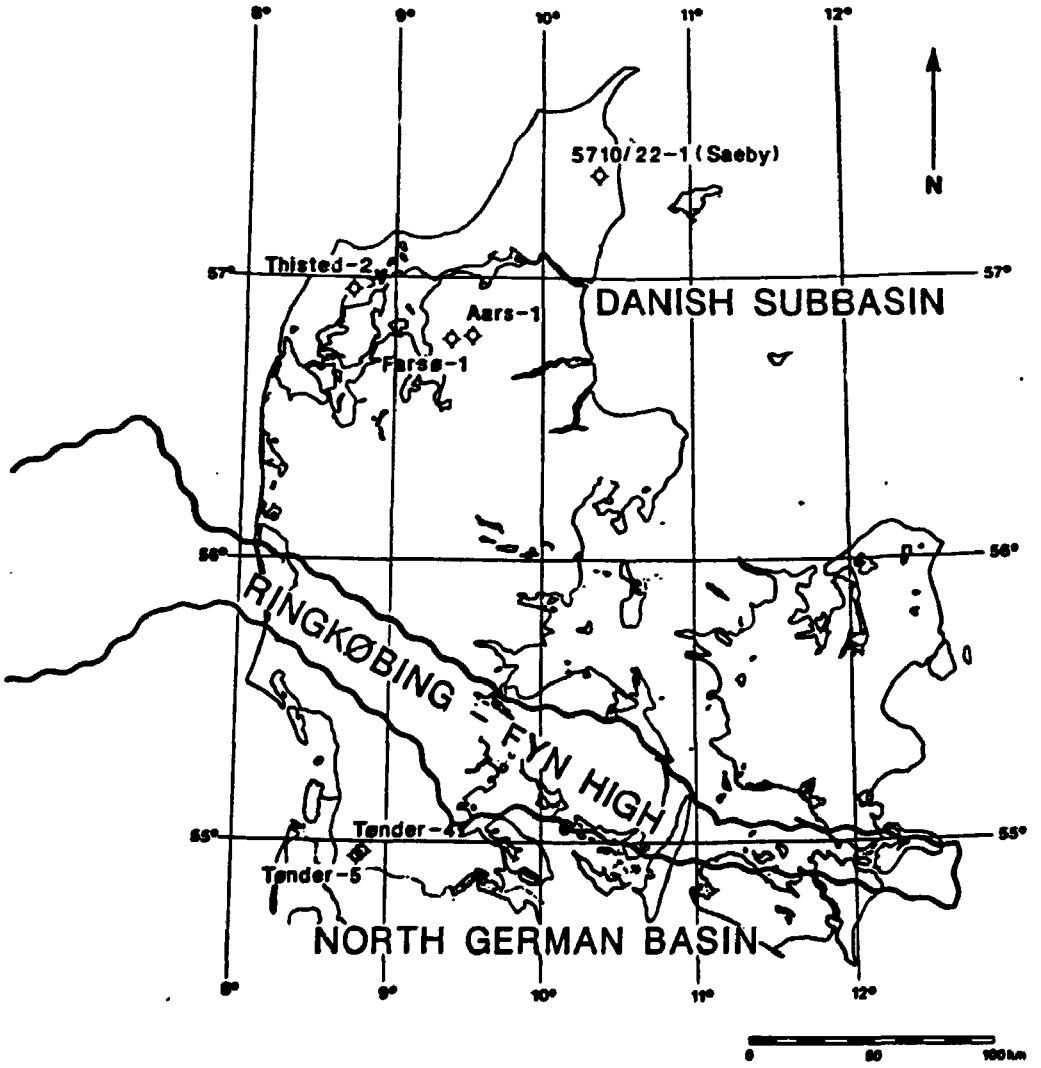


Figure 1

Location map of the five wells investigated in the Danish Subbasin and in the North German Basin. Wash-out experiments were carried out on samples from well 5710/22-1 (Sæby).

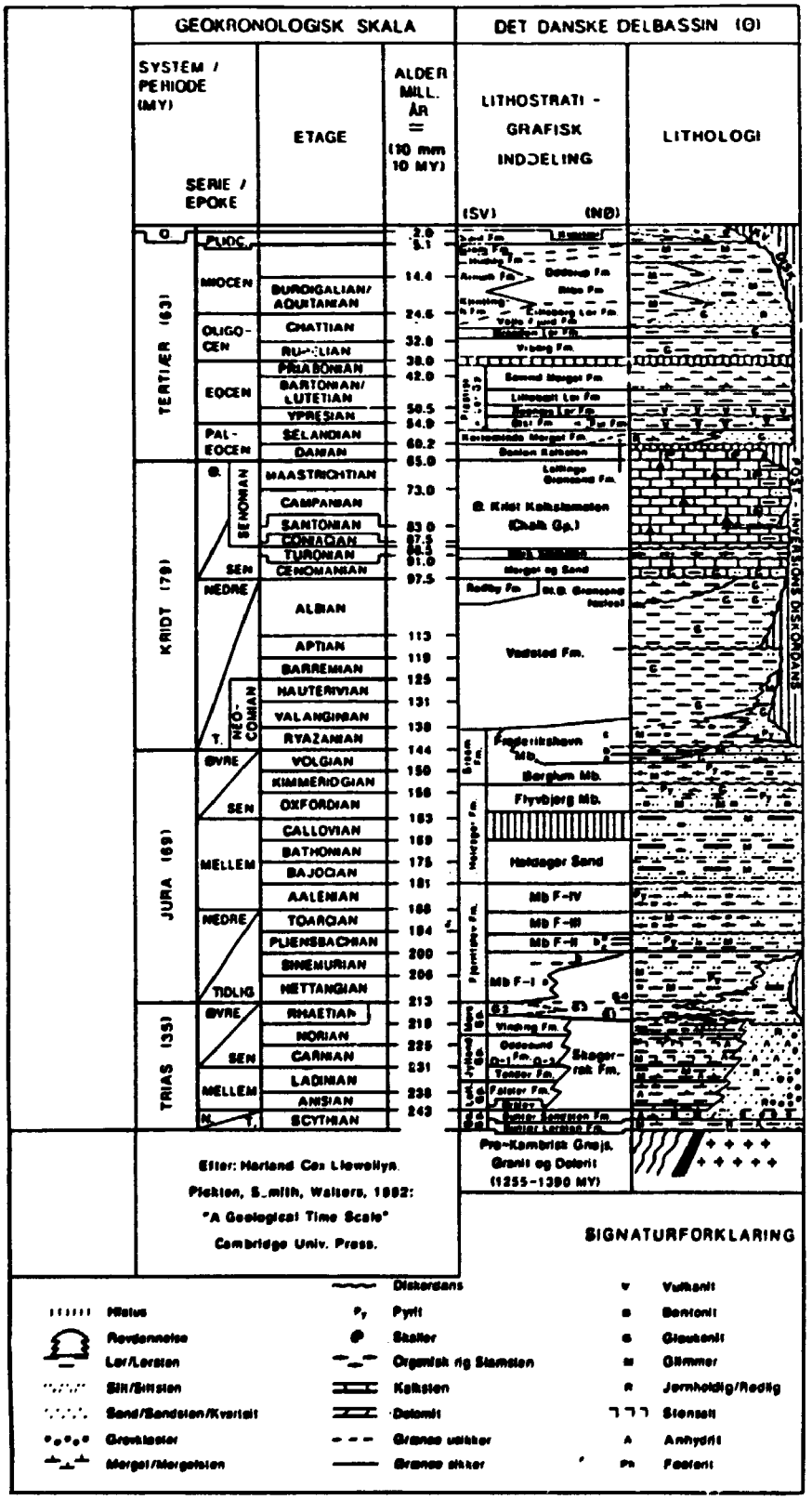


Figure 2

Chronostratigraphy, lithostratigraphy and lithology of the Danish Subbasin. The lithostratigraphy of the Triassic formations is applicable also for the part of the North German Basin in question.

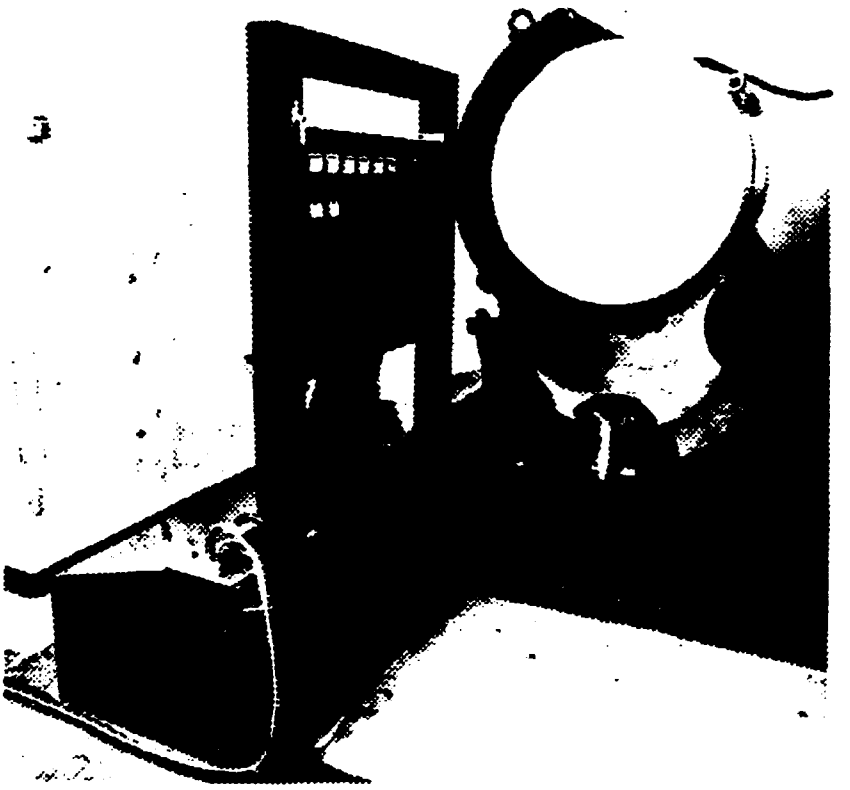


Figure 3

Automatical laboratory spectrometer used for sealed-can gamma-ray analysis of U-Th-K concentrations in cutting samples.

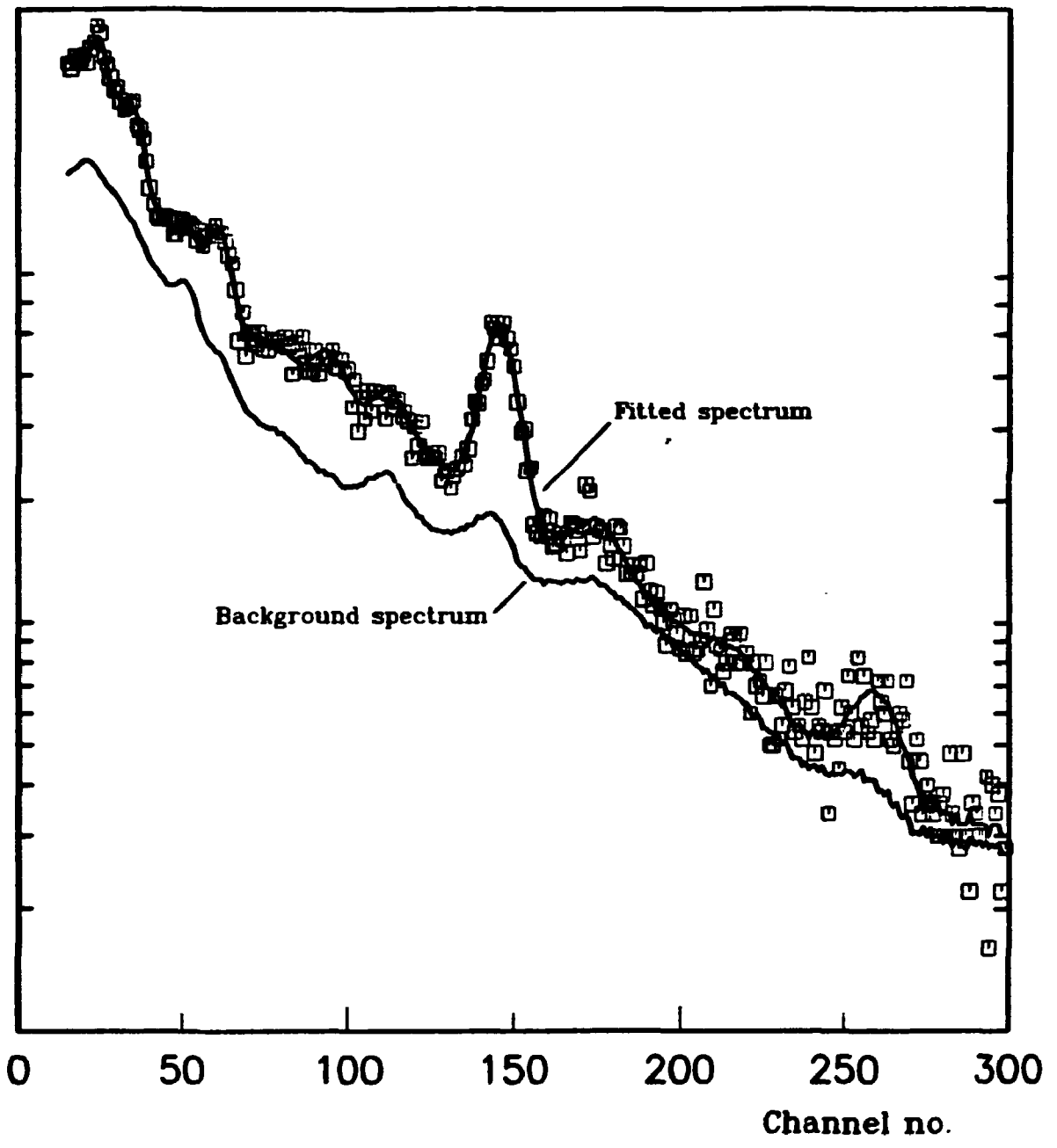


Figure 4

Experimental gamma-ray spectra (cutting sample and background) recorded with the laboratory spectrometer. The sample had a net weight of 245 grams, and the fitted spectrum suggests that it contains 1.98 ±0.08 ppm eU, 4.83 ±0.19 ppm Th, and 0.931 ±0.029 % K.

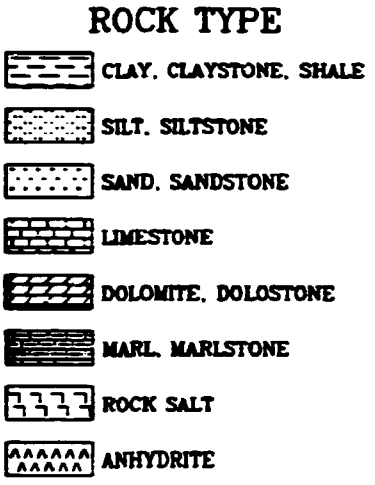
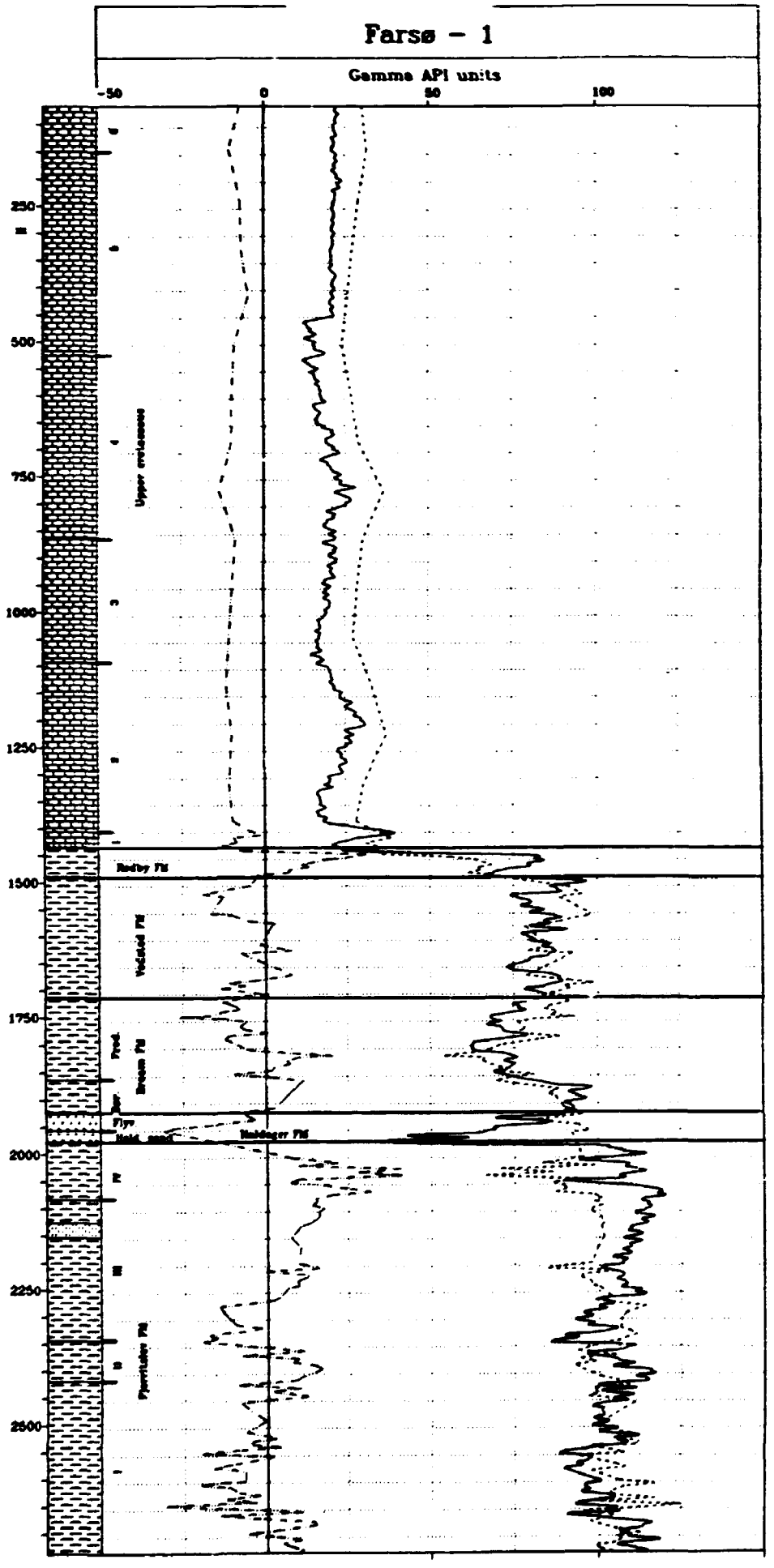
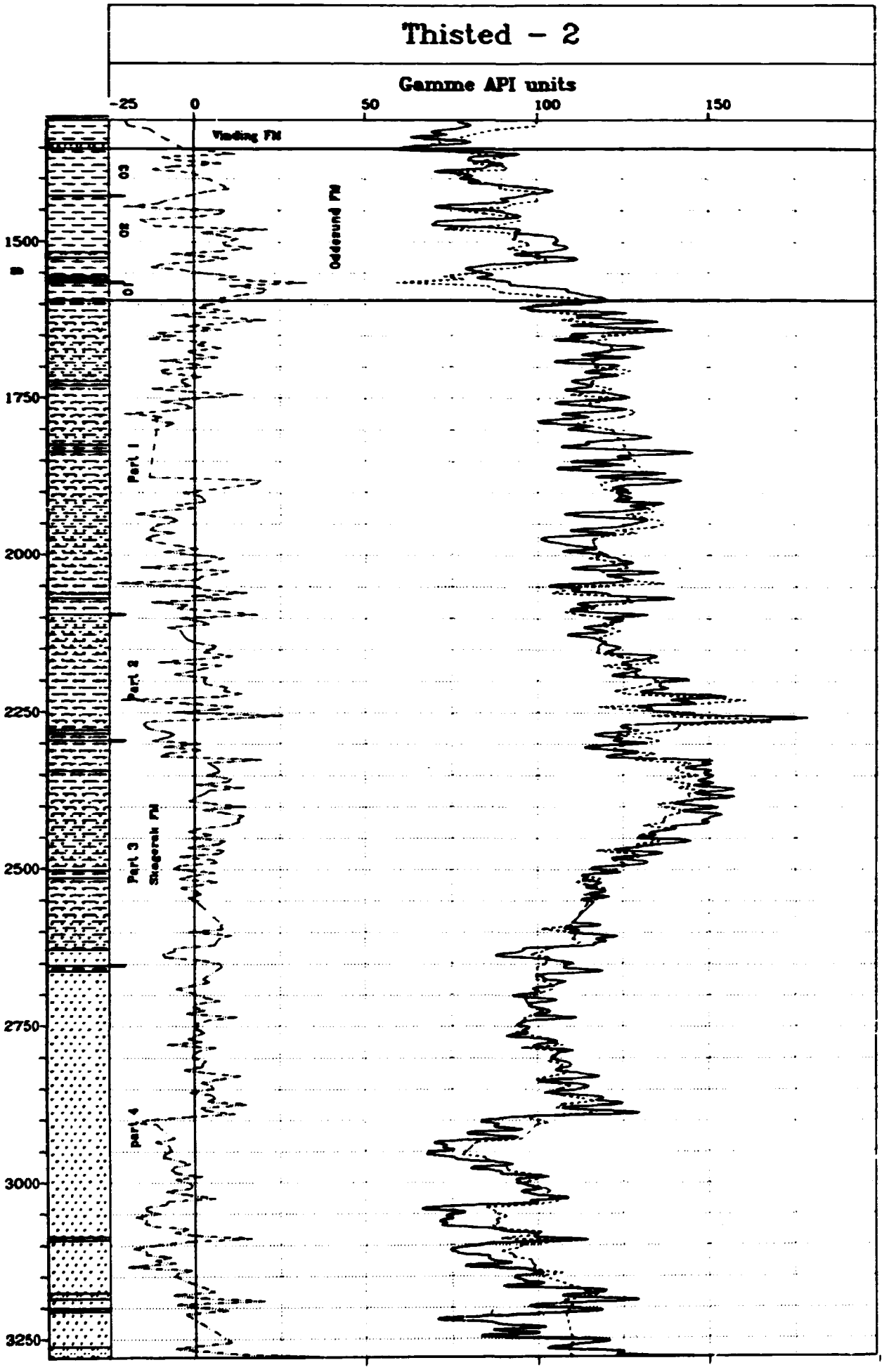
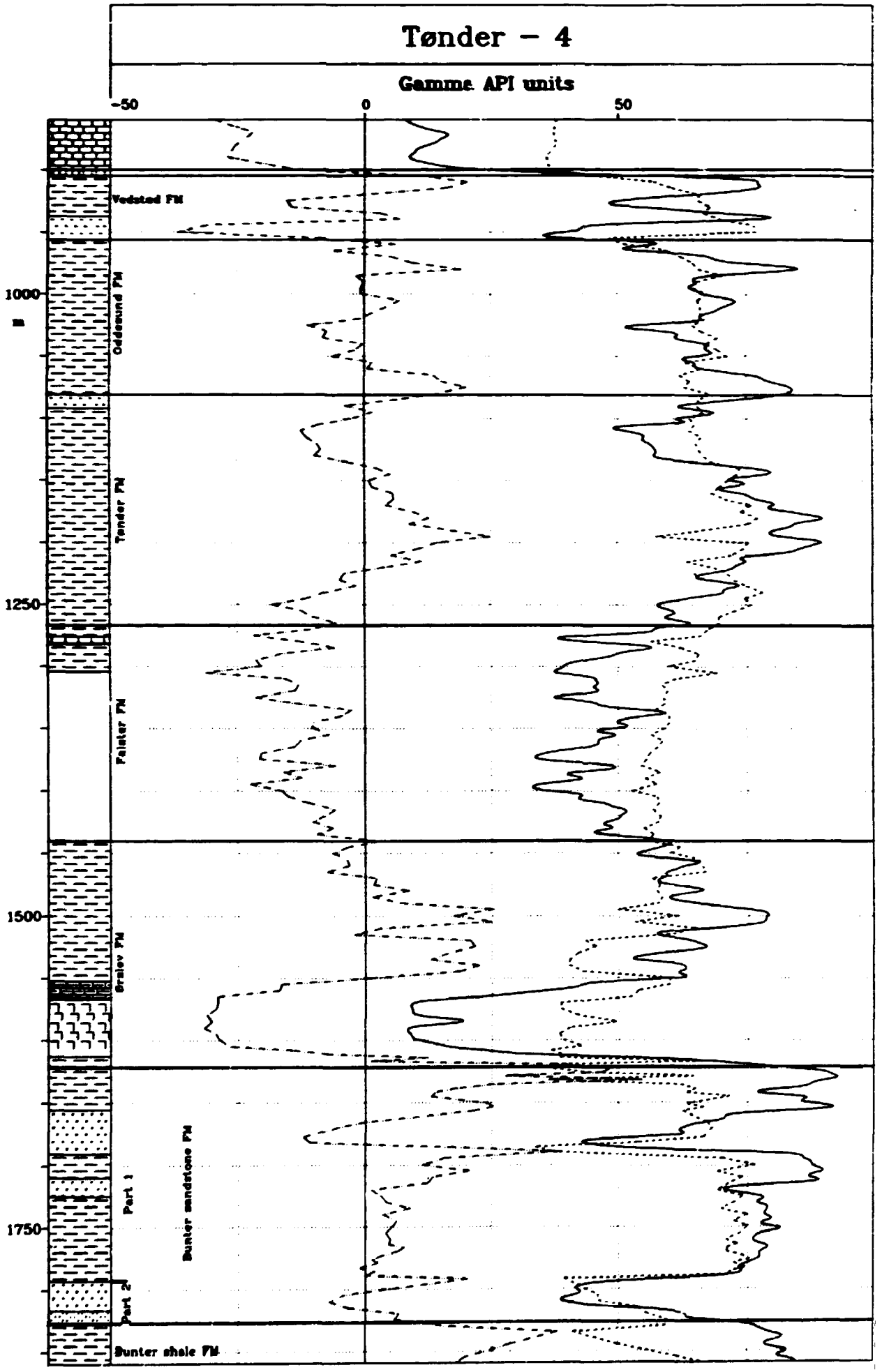


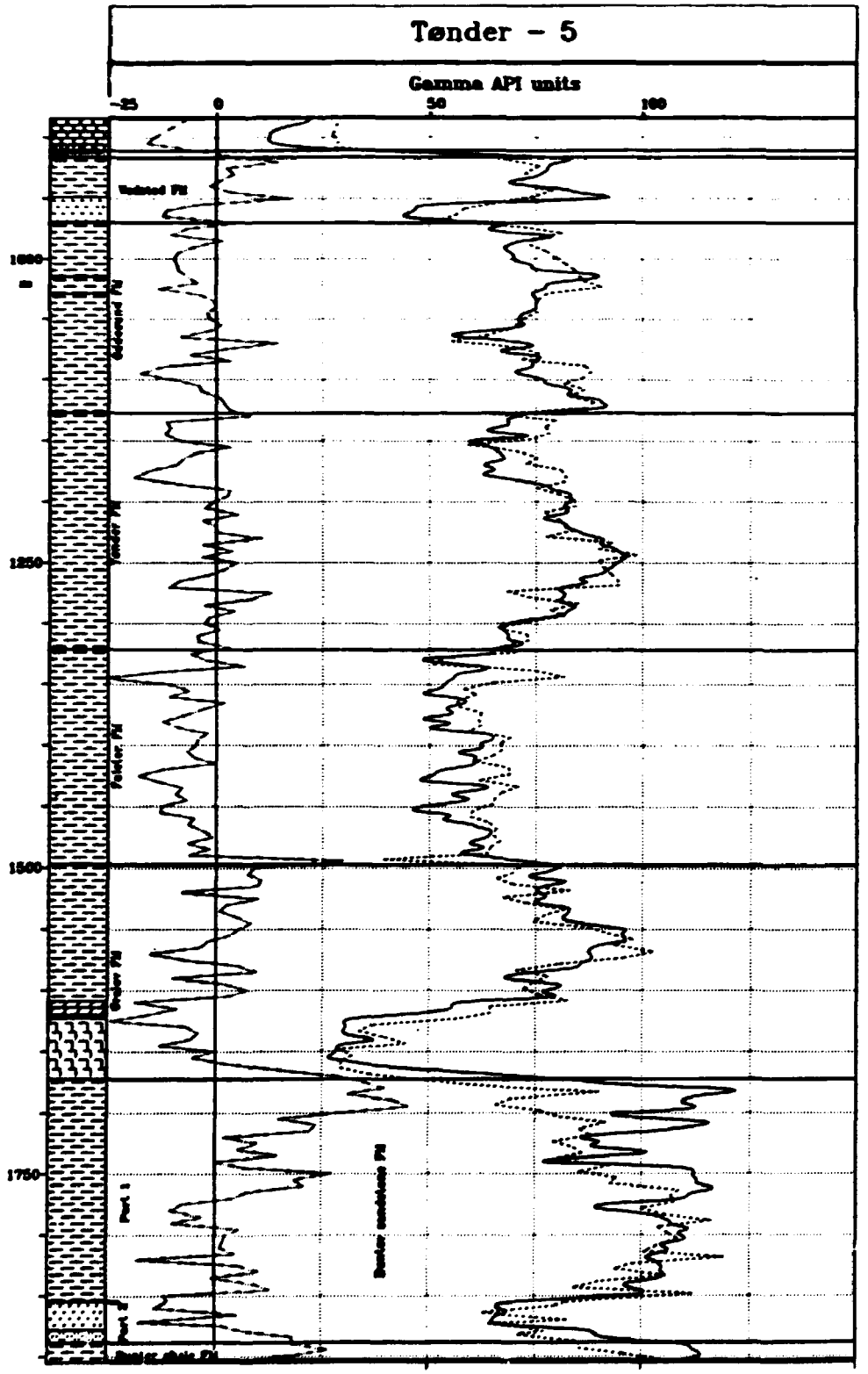
Figure 5-8

Total radioelement abundance logs for the wells Farsø-1, Thisted-2, Tønder-4 and Tønder-5.
Solid curve: Wireline total gamma-ray log after smoothing.
Dashed curve: Geochemical log calculated from the radioelement concentrations in bulk cutting samples.
Dot-and-dash curve: Deviation between these two logs.
Boundaries between sub-ordinate lithological units are shown with bars.


Farsø - 1
Gamme API units
-50
0
50
100
250
m
500
750
1000
1250
1500
1750
2000
2250
2500
Upper evisessus
Rødby Fm
Vedsted Fm
Prod.
Brøm Fm
Flyv
Hidd. sand
Hidsager Fm
Plenerlutite Fm


Thisted - 2
Gamme API units
-25
0
50
100
150
Vinding Fm
Oddesund Fm
Part 1
Part 2
Part 3
Stagerak Fm
part 4
1500
1750
2000
2250
2500
2750
3000
3250


Tønder – 4
Gamme API units
-50
0
50
Vedstad FM
Oddesund FM
Tønder FM
Palæt FM
Bryløv FM
Part 1
Bunter sandstone FM
Part 2
Bunter shale FM
1000
m
1250
1500
1750


Tønder - 5
Gamma API units
-25
0
50
100
1000
m
1250
1500
1750

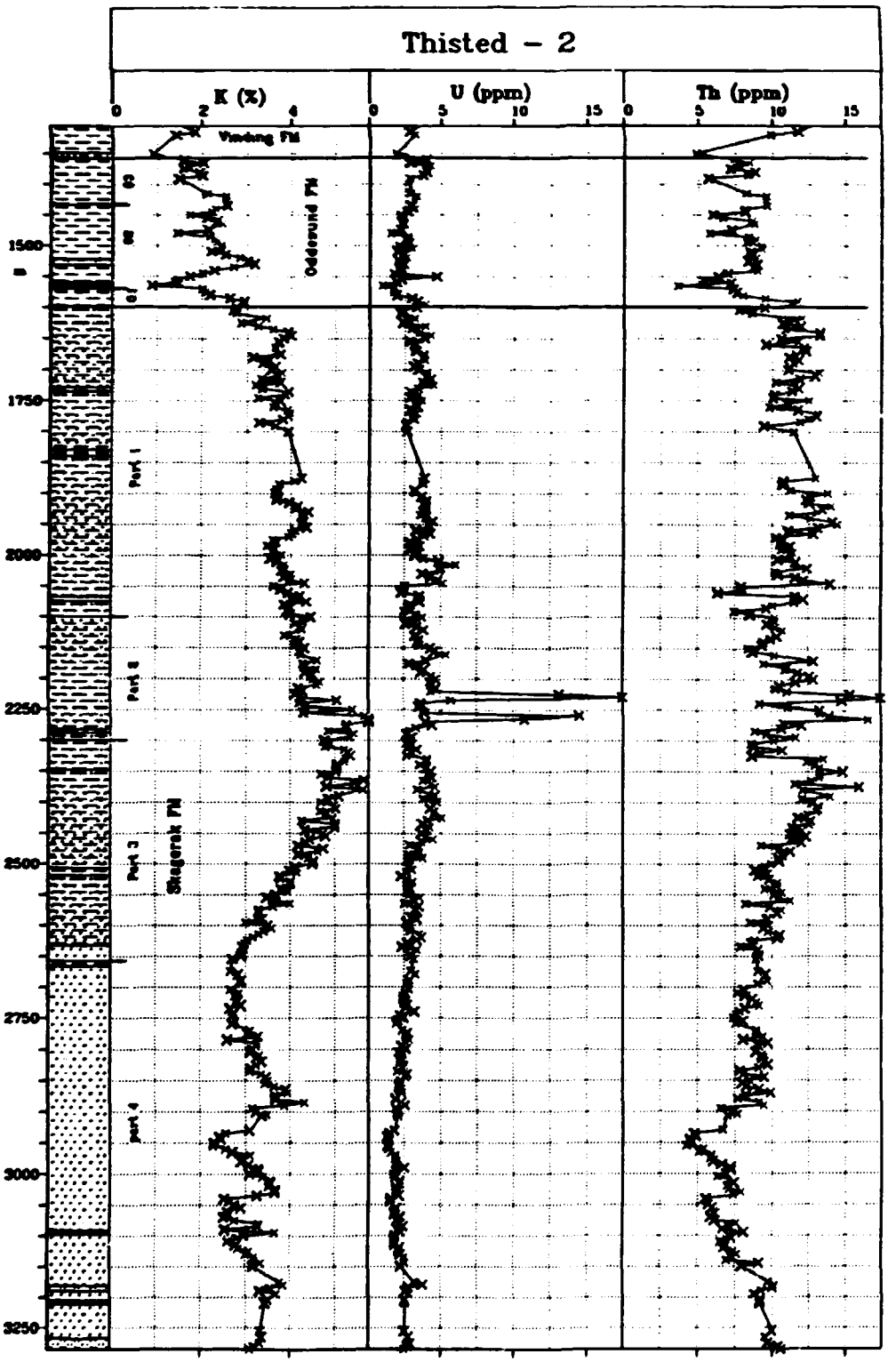


Figure 9

Radioelement abundance logs on the basis of gamma-ray spectrometry of bulk cutting samples from Thisted-2.

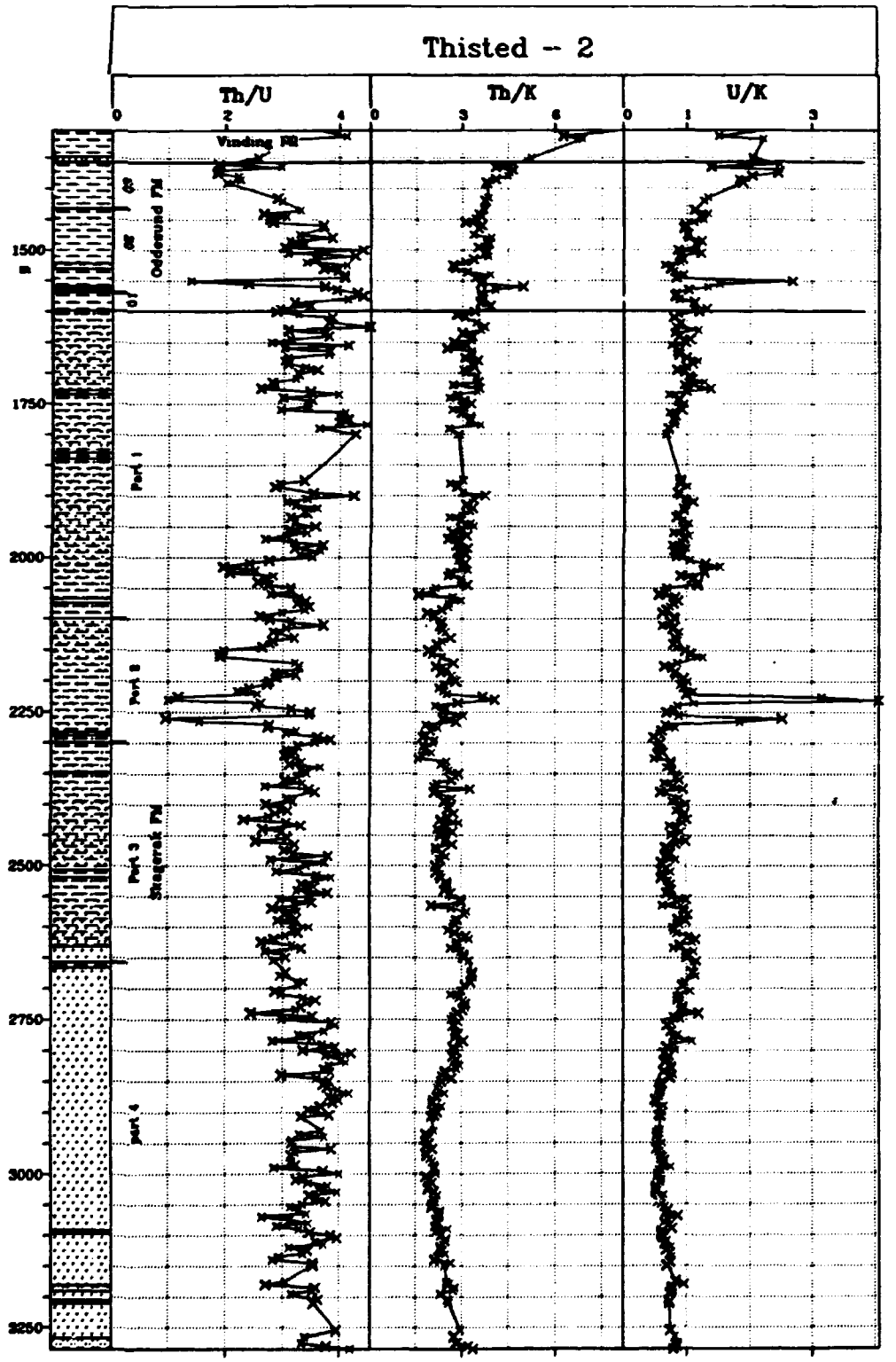


Figure 10

Radioelement ratio logs from Thisted-2.

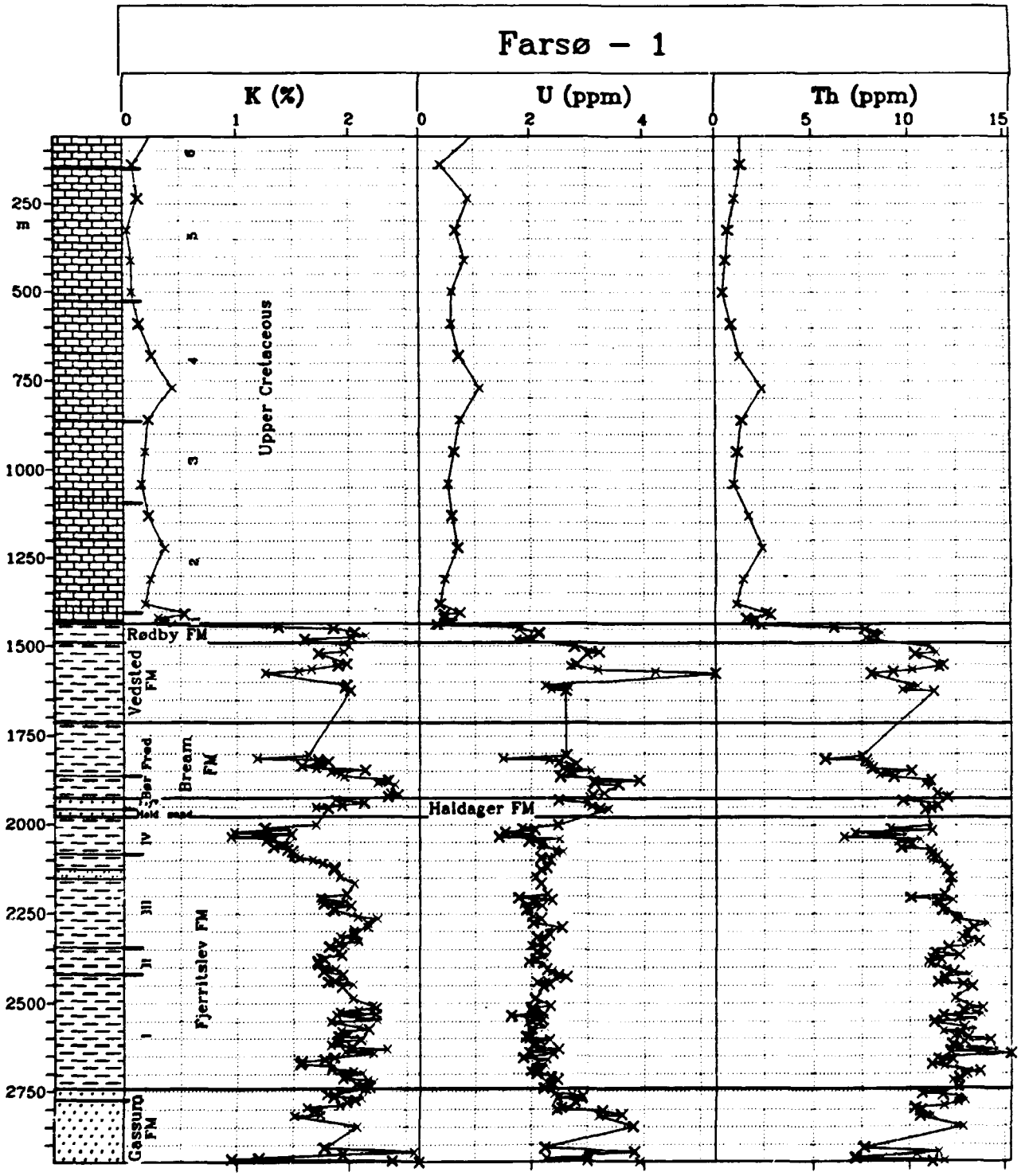


Figure 11

Radioelement abundance logs on the basis of gamma-ray spectrometry of bulk cutting samples from Farsø-1.

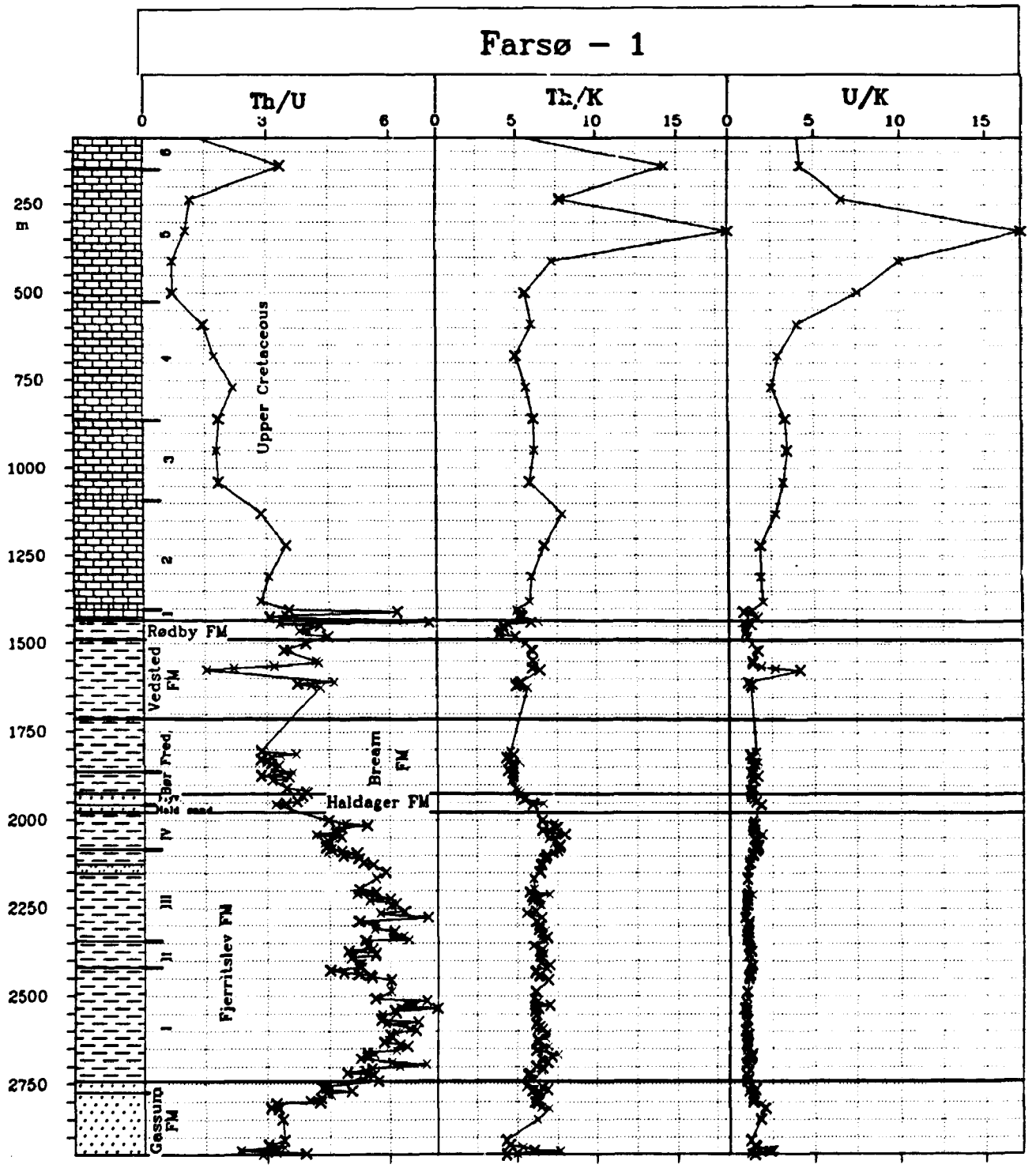


Figure 12

Radioelement ratio logs from Farsø-1.

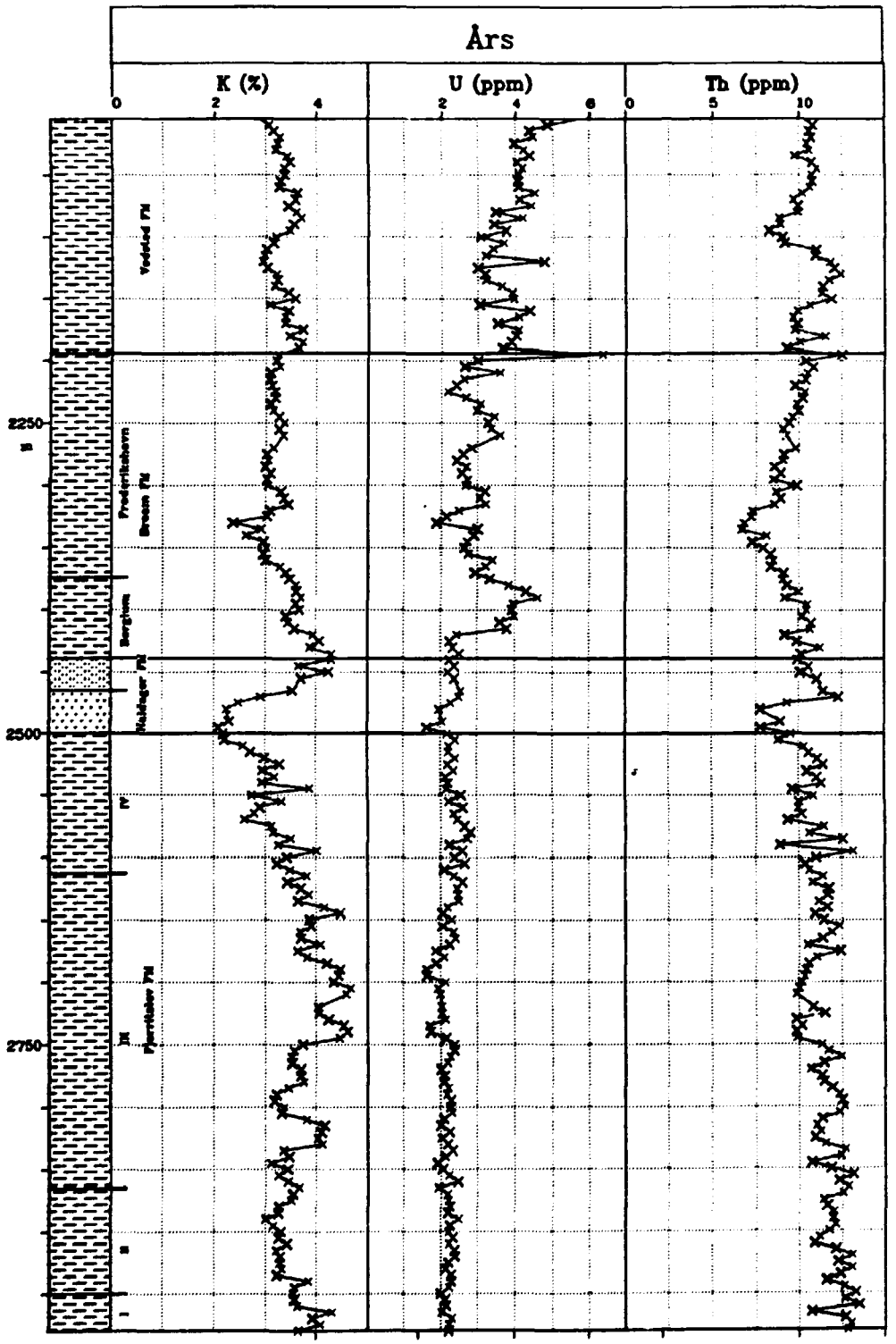


Figure 13

Radioelement abundance logs on the basis of gamma-ray spectrometry of bulk cutting samples from Aars-1.

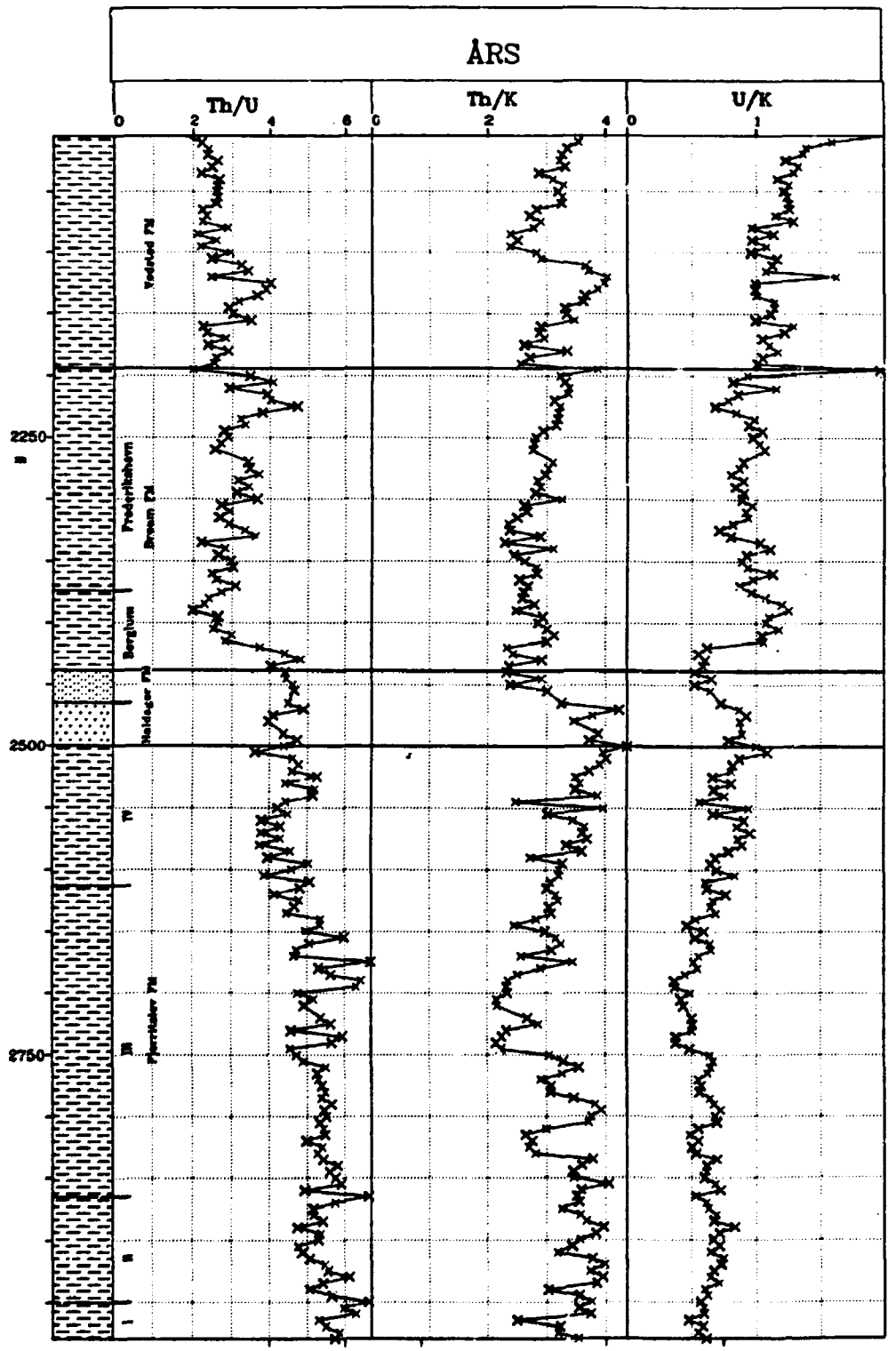


Figure 14

Radioelement ratio logs from Aars-1.

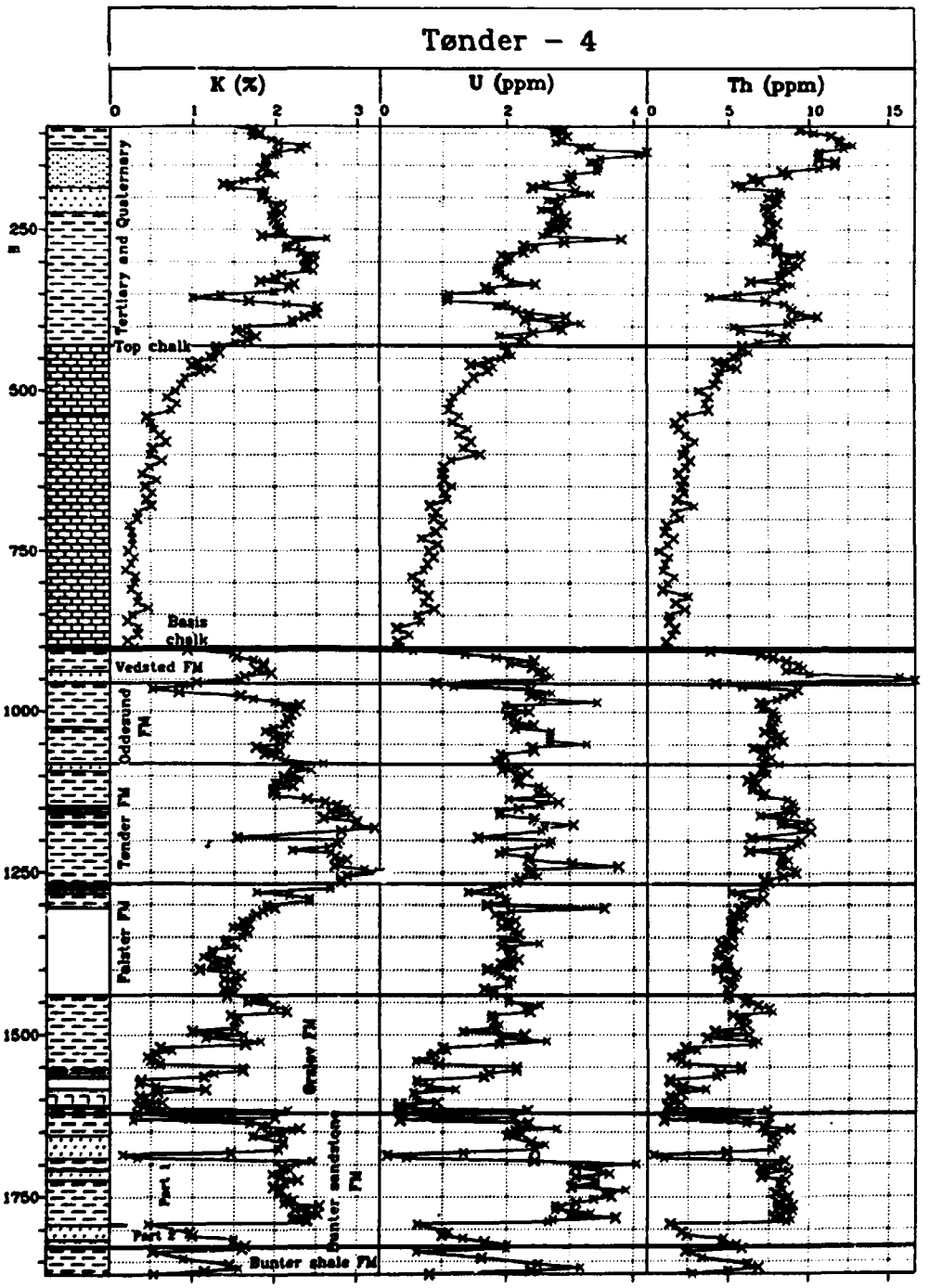


Figure 15

Radioelement abundance logs on the basis of gamma-ray spectrometry of bulk cutting samples from Tønder-4.

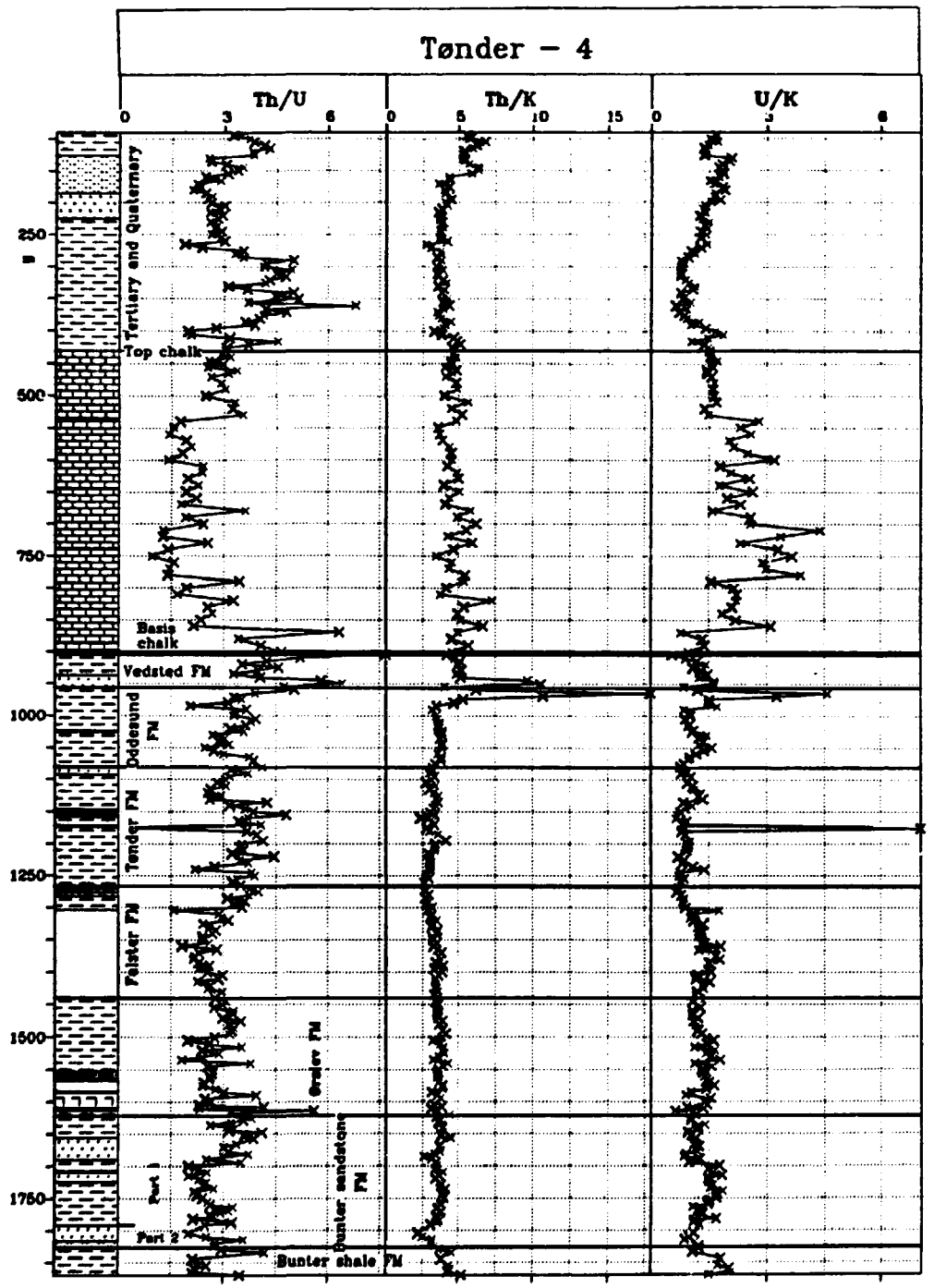


Figure 16

Radioelement ratio logs from Tønder-4.

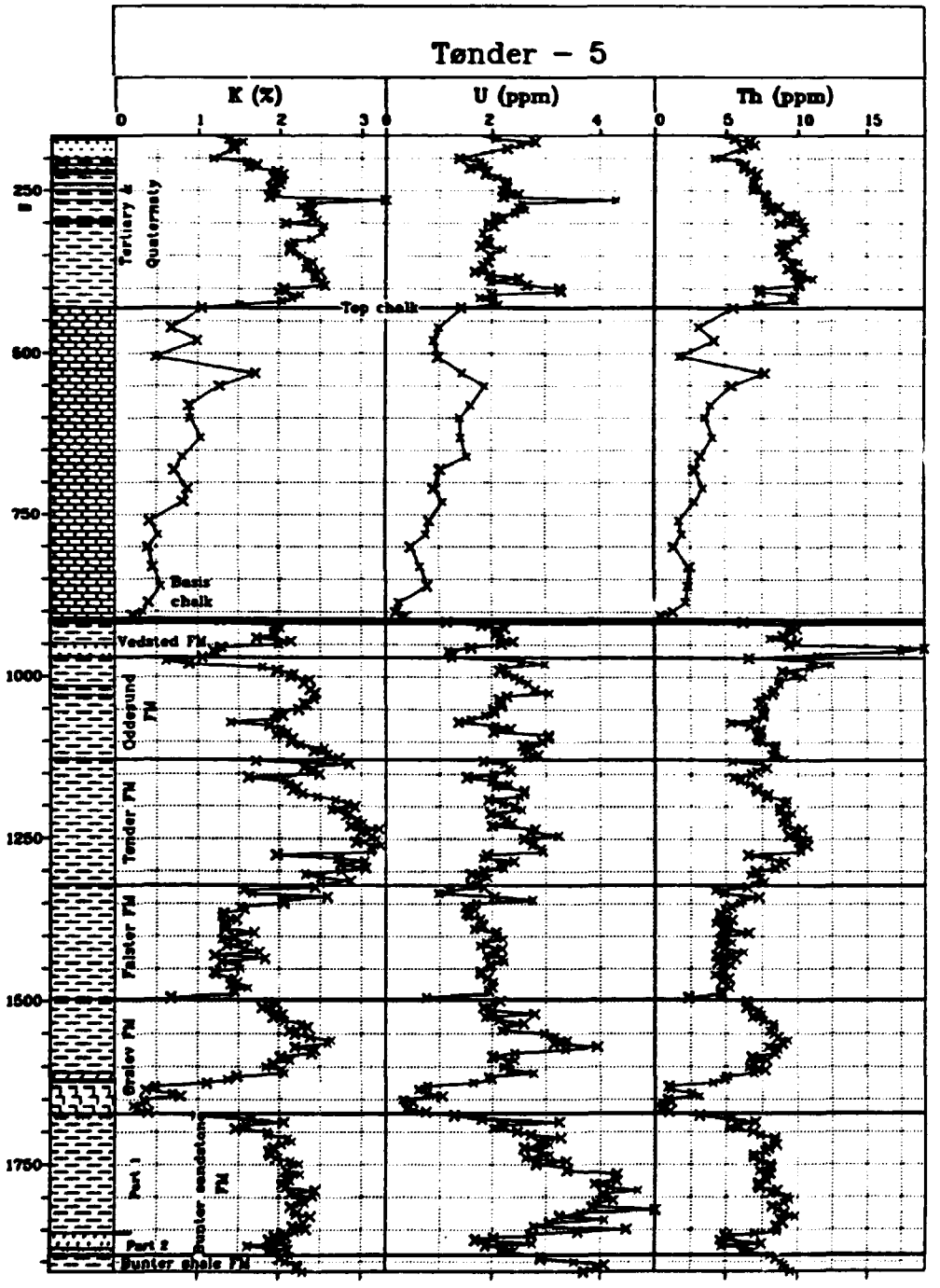
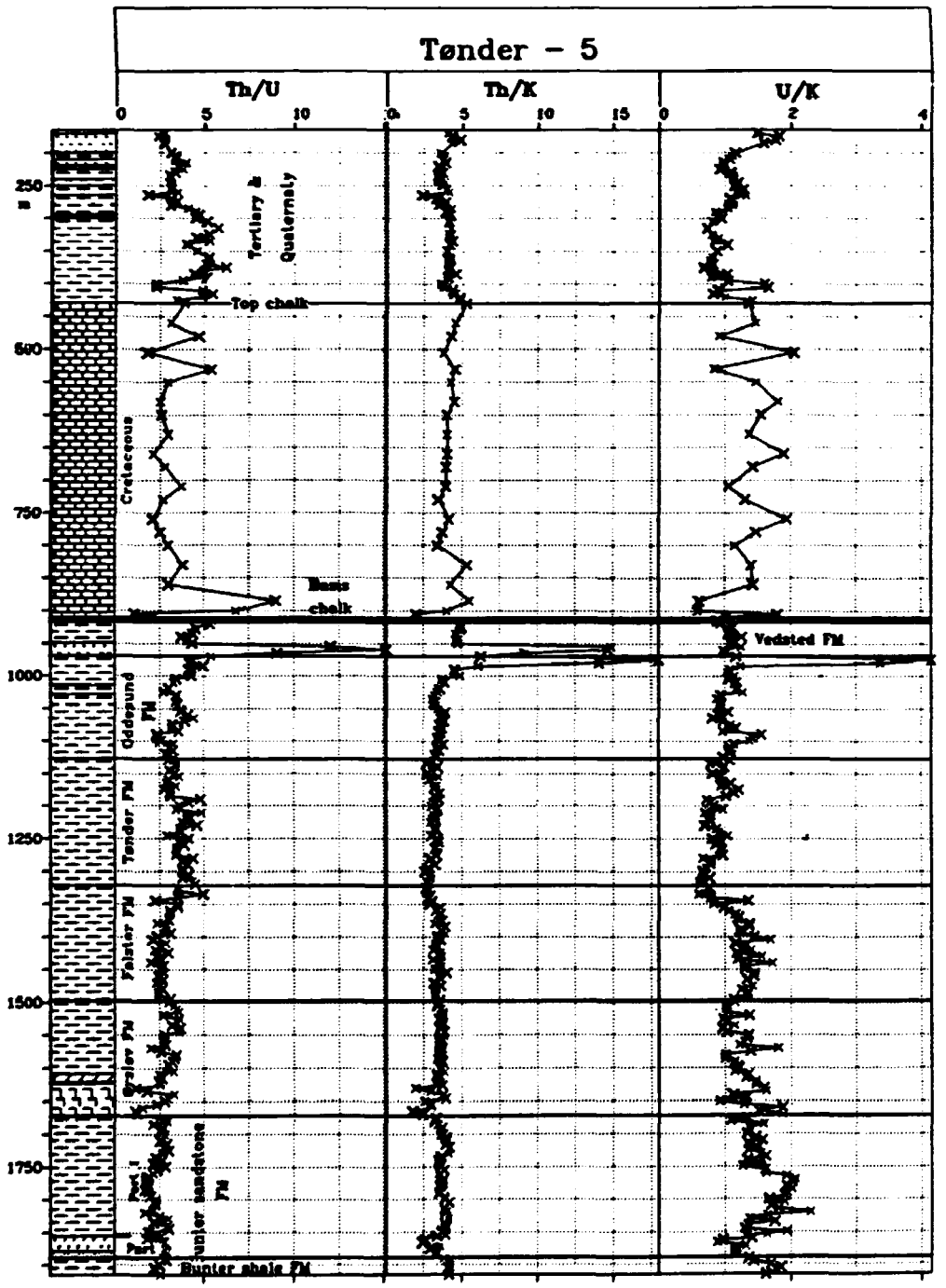


Figure 17

Radioelement abundance logs on the basis of gamma-ray spectrometry of bulk cutting samples from Tønder-5.


Tønder - 5
Th/U
Th/K
U/K
0
5
10
15
2
4
250
m
500
750
1000
1250
1500
1750
Tertiary & Quaternary
Top chalk
Cretaceous
Base chalk
Vedsted FM
Oddepund FM
Tønder FM
Falster FM
Gassum FM
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8
Unit 9
Unit 10
Unit 11
Unit 12
Unit 13
Unit 14
Unit 15
Unit 16
Unit 17
Unit 18
Unit 19
Unit 20
Unit

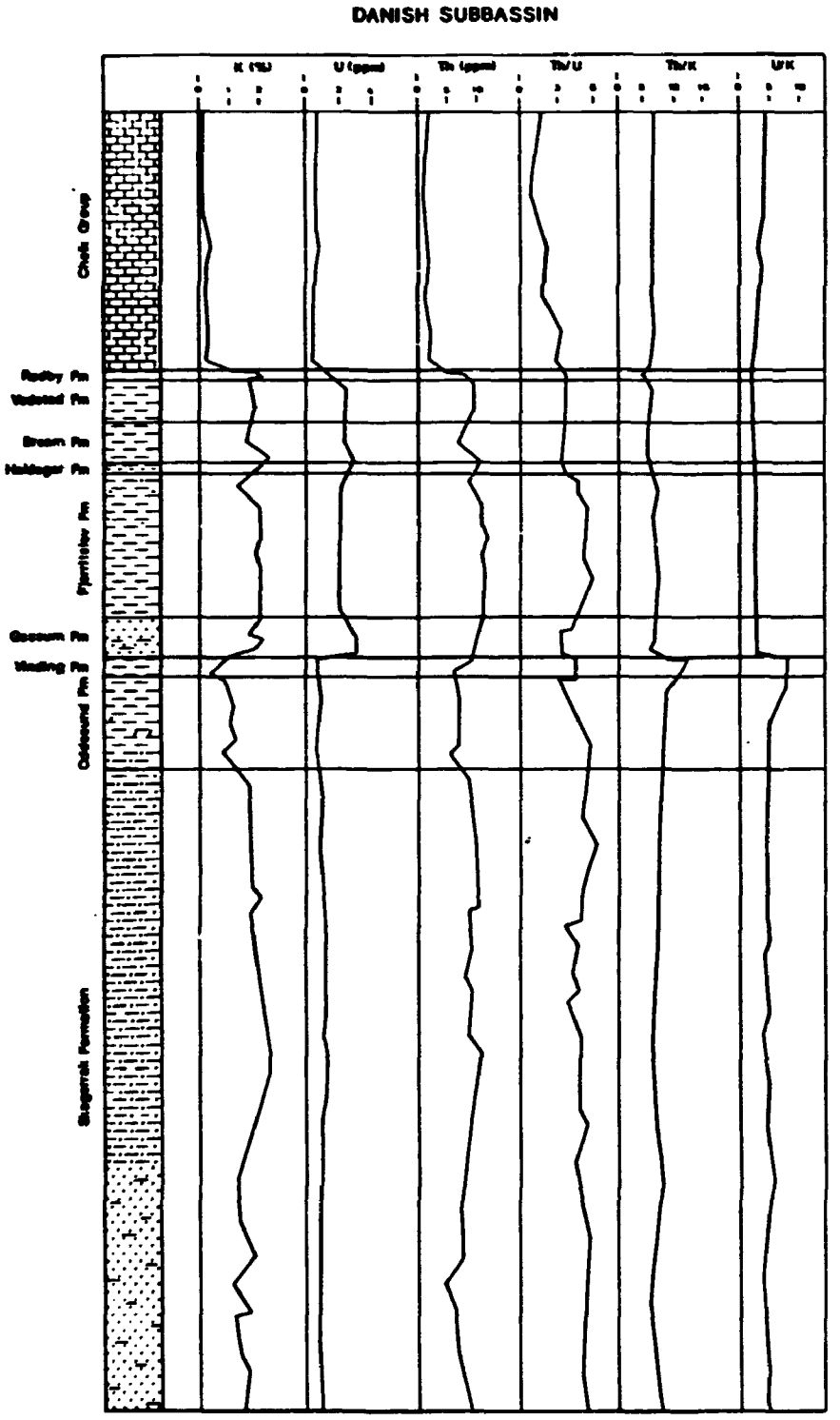


Figure 19

K, U, Th reference profile for the central part of the Danish Subbasin. The radioelement abundance logs and ratio logs are smoothed values combined from the wells Aars-1, Farsø-1 and Thisted-2. The logs are related to lithostratigraphy and not to the depth.

Figure 20

U - Th/U cross plot of average analytical values from litho-stratigraphical units in the Danish Subbasin and the North German Basin. Each calculated point is shown with a range given by plus minus one standard deviation, and the numbers refer to the following units:

Farsø-1 (1-10); Chalk gr. (1), Vedsted Fm. (2), Bream Fm. Frh. Mb. (3), Bream Fm. Børglum Mb. (4), Fjerritslev Fm. (5), F-IV Mb. (6), F-III Mb. (7), F-II Mb. (8), F-I Mb. (9), Gassum Fm. (10).

Aars-1 (11-17); Vedsted Fm. (11), Bream Fm. Frh. Mb. (12), Bream Fm. Børglum Mb. (13), Fjerritslev Fm. (F-IV Mb. (14), F-III Mb. (15), F-II Mb. (16), F-I Mb. (17).

Thisted-2 (18-23); Oddesund Fm. (18), Skagerrak Fm. (19), Skg Fm. 1600-2100 m (20), Skg Fm. 2100-2300 m (21), Skg Fm. 2300-2650 m (22), Skg Fm. 2650-3285 m (23).

Tønder-4 (24-33); Quat. and Tert. (24), Chalk gr. (25), Vedsted Fm. (26), Oddesund Fm. (27), Tønder Fm. (28), Falster Fm. (29), Ørslev Fm. (30), Bunter Sd. Fm. (31), Bunter Sd. Fm. 1690-1783 m (32), Bunter Sd. Fm. 1786-1825 m (33).

Tønder-5 (34-42); Quat. and Tert. (34), Chalk gr. (35), Vedsted Fm. (36), Oddesund Fm. (37), Tønder Fm. (38), Falster Fm. (39), Bunter Sd. Fm. (40), Bunter Sd. Fm. 1745-1854 m (41), Bunter Sd. Fm. 1857-1890 m (42).

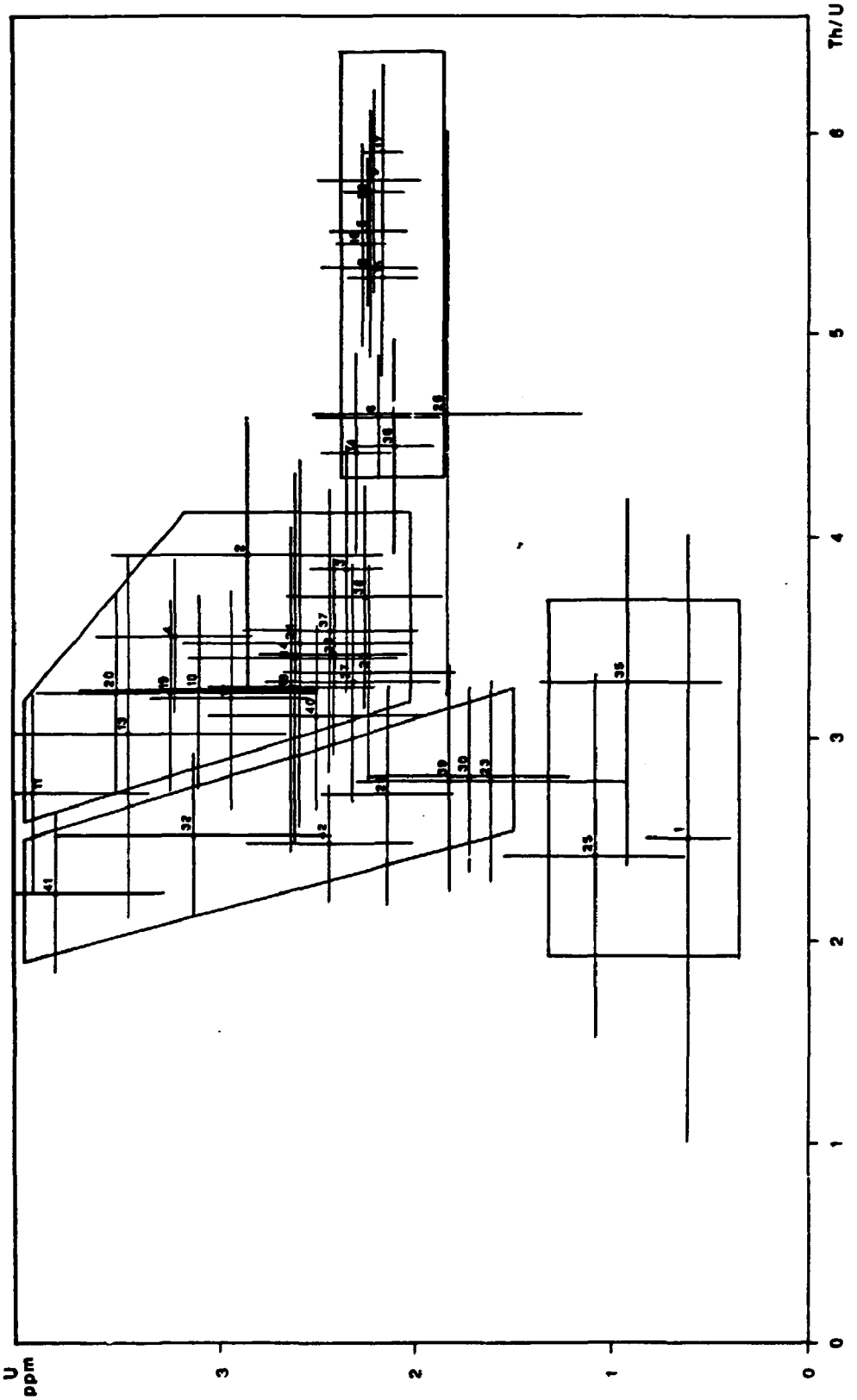


Figure 20

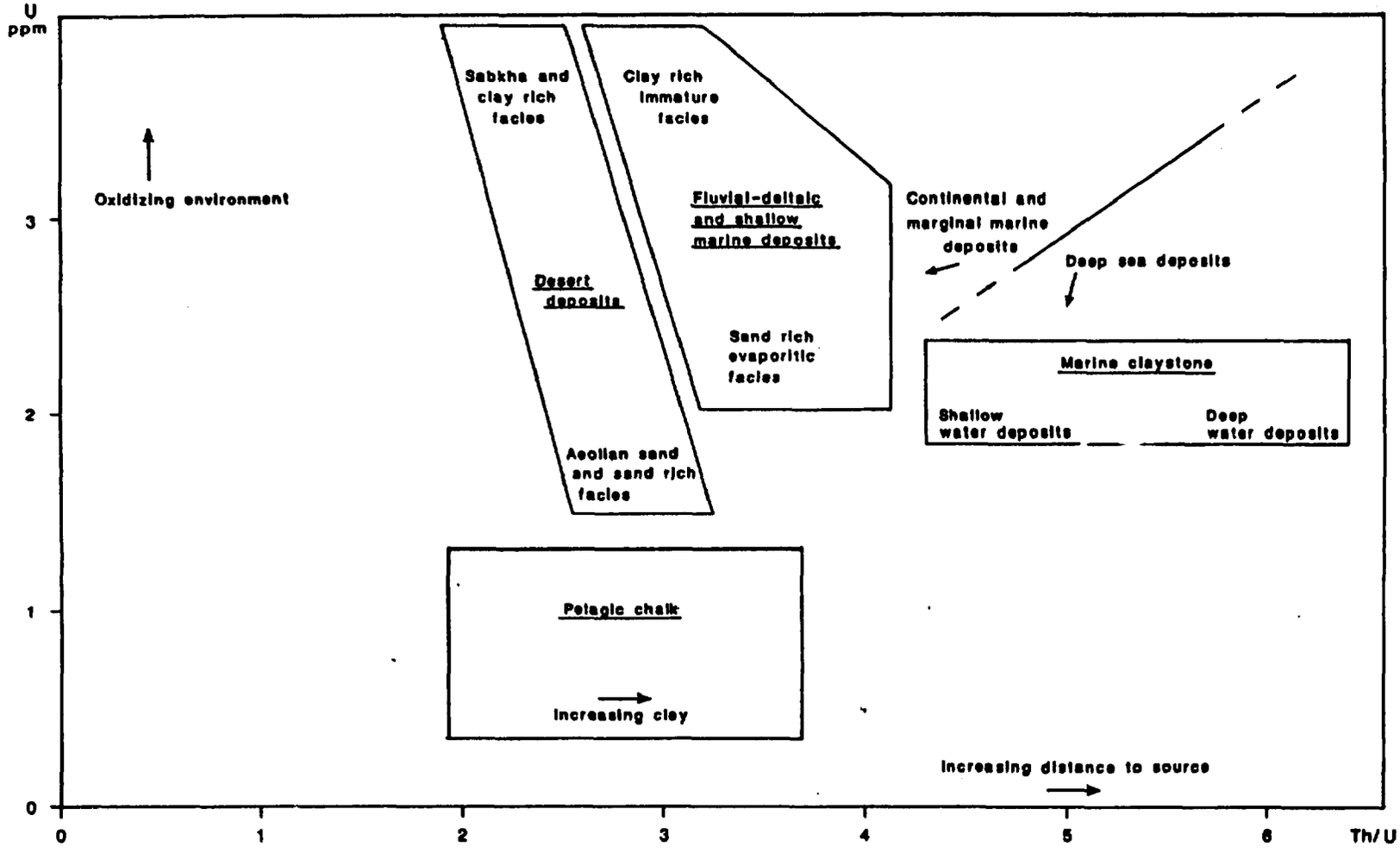


Figure 21

Relationship between U - Th/U and major lithofacies groups in the Danish Subbasin and the North German Basin. The depositional-geochemical model has been constructed on the basis of the cross plot in Figure 20.

APPENDIX

Farsø - 1

	Unit no	Number of samples	K(%) Min-Max Mean(std)	U(ppm) Min-Max Mean(std)	Th(ppm) Min-Max Mean(std)	U/K Min-Max Mean(std)	Th/K Min-Max Mean(std)	Th/U Min-Max Mean(std)
Chalk	1	21	0.04-0.5 0.3 (0.1)	0.3-1.1 0.6 (0.2)	0.4-2.9 1.5 (0.7)	0.9-17 4.0 (3.8)	5-18 7.0 (3.2)	0.7-6.3 2.6 (1.5)
Vedsted Fm	2	20	1.3-2.0 1.8 (0.2)	2.2-5.3 2.8 (0.7)	8.0-11.8 10.5 (1.0)	1.1-4.2 1.6 (0.7)	5.0-6.4 5.8 (0.4)	1.5-5.0 3.9 (0.9)
Brejning Fm, Frederikshavn Mb	3	26	1.2-2.1 1.8 (0.2)	1.5-3.1 2.4 (0.3)	5.6-11.4 9.0 (1.3)	1.1-1.7 1.4 (0.2)	4.3-6.1 5.2 (0.5)	2.8-5.2 3.8 (0.7)
Brejning Fm, Børglum Mb	4	8	2.0-2.4 2.3 (0.2)	2.5-3.9 3.2 (0.4)	9.2-12.2 11.1 (0.9)	1.3-1.7 1.4 (0.1)	4.6-5.2 4.8 (0.2)	2.8-4.0 3.5 (0.4)
Fjerritslev Fm	5	99	0.9-2.3 1.9 (0.3)	1.4-2.9 2.2 (0.2)	6.6-15.3 12.1 (1.3)	0.9-1.9 1.2 (0.2)	5.6-8.0 6.5 (0.5)	4.2-7.2 5.6 (0.7)
Fjerritslev Fm, F-IV	6	14	0.9-1.7 1.4 (0.2)	1.4-2.6 2.1 (0.4)	6.6-11.4 9.9 (1.5)	1.4-1.9 1.6 (0.1)	6.5-8.0 7.3 (0.4)	4.2-5.4 4.6 (0.3)
Fjerritslev Fm, F-III	7	28	1.5-2.2 1.9 (0.2)	1.8-2.6 2.2 (0.2)	10.0-14.1 12.3 (0.9)	0.9-1.6 1.1 (0.2)	5.6-7.6 6.4 (0.4)	4.8-6.9 5.7 (0.5)
Fjerritslev Fm, F-II	8	8	1.7-1.9 1.8 (0.1)	2.0-2.4 2.2 (0.1)	11.0-12.6 11.7 (0.6)	1.1-1.3 1.2 (0.1)	6.0-7.0 6.5 (0.3)	5.0-5.6 5.3 (0.3)
Fjerritslev Fm, F-I	9	49	1.6-2.3 2.0 (0.2)	1.7-2.9 2.2 (0.2)	10.6-15.3 12.6 (0.9)	0.9-1.6 1.1 (0.2)	5.6-7.5 6.4 (0.4)	4.3-7.2 5.8 (0.7)
Gassum Fm	10	10	1.0-2.6 1.7 (0.5)	2.2-3.8 3.1 (0.6)	7.1-12.9 10.0 (2.0)	1.3-2.6 1.9 (0.4)	4.3-7.6 6.0 (1.0)	2.4-4.3 3.3 (0.5)

Ars - 1

	Unit no	Number of samples	K(%) Min-Max Mean(std)	U(ppm) Min-Max Mean(std)	Th(ppm) Min-Max Mean(std)	U/K Min-Max Mean(std)	Th/K Min-Max Mean(std)	Th/U Min-Max Mean(std)
Vedsted Fm	11	38	2.9-3.7 3.3 (0.2)	3.0-5.7 4.0 (0.6)	8.2-12.4 10.4 (1.0)	1.0-2.0 1.2 (0.2)	2.4-4.0 3.2 (0.4)	1.8-4.0 2.7 (0.5)
Bream Fm, Frederikshavn Mb	12	35	2.4-3.4 3.1 (0.2)	1.9-6.3 3.0 (0.7)	6.7-12.5 9.1 (1.3)	0.7-2.0 1.0 (0.2)	2.3-3.9 2.9 (0.4)	2.0-4.7 3.2 (0.6)
Bream Fm, Børglum Mb	13	13	3.4-4.3 3.7 (0.3)	2.3-4.6 3.5 (0.8)	9.1-11.3 10.1 (0.7)	0.6-1.3 1.0 (0.3)	2.3-3.1 2.7 (0.3)	2.0-4.8 3.1 (0.9)
Fjerritslev Fm, F-IV	14	23	2.2-4.0 3.1 (0.5)	2.1-2.8 2.4 (0.2)	8.8-13.2 10.6 (1.1)	0.6-1.1 0.8 (0.1)	2.5-4.4 3.5 (0.4)	3.6-5.2 4.5 (0.5)
Fjerritslev Fm, F-III	15	50	3.1-4.7 3.8 (0.4)	1.6-2.6 2.2 (0.2)	9.9-13.2 11.4 (0.9)	0.4-0.8 0.6 (0.1)	2.1-4.1 3.0 (0.5)	4.1-6.7 5.3 (0.5)
Fjerritslev Fm, F-II	16	18	3.0-3.8 3.4 (0.2)	1.9-2.5 2.2 (0.1)	10.9-13.3 12.2 (0.7)	0.5-0.8 0.7 (0.1)	3.0-4.0 3.6 (0.3)	4.8-6.6 5.5 (0.6)
Fjerritslev Fm, F-I	17	7	3.5-4.3 3.8 (0.3)	2.0-2.3 2.2 (0.1)	10.8-13.5 12.7 (0.9)	0.5-0.6 0.6 (0.1)	2.5-3.8 3.4 (0.4)	5.3-6.6 5.9 (0.5)

Thisted - 2

	Unit no	Number of samples	K(%) Min-Max Mean(std)	U(ppm) Min-Max Mean(std)	Th(ppm) Min-Max Mean(std)	U/K Min-Max Mean(std)	Th/K Min-Max Mean(std)	Th/U Min-Max Mean(std)
Oddesund Fm	18	41	0.9-3.2 2.2 (0.5)	0.9-4.6 2.7 (0.8)	3.6-11.7 8.0 (1.5)	0.7-2.7 1.3 (0.5)	2.7-5.0 3.7 (0.5)	1.4-4.4 3.2 (0.8)
Skagerak Fm	19	294	2.3-5.9 3.8 (0.8)	1.3-17.5 3.2 (1.6)	4.3-17.5 10.0 (2.3)	0.5-4.1 0.8 (0.3)	1.6-4.1 2.6 (0.5)	1.0-4.5 3.3 (0.5)
Skagerak Fm, part 1	20	84	2.7-4.5 3.8 (0.4)	2.2-6.0 3.5 (0.7)	6.4-14.4 11.3 (1.6)	0.6-1.5 0.9 (0.2)	1.6-3.7 3.0 (0.4)	2.0-4.5 3.3 (0.5)
Skagerak Fm, part 2	21	39	3.9-5.9 4.7 (0.5)	2.6-17.5 4.8 (3.3)	8.4-17.5 11.3 (2.1)	0.5-4.1 1.0 (0.7)	1.7-4.1 2.4 (0.5)	1.0-3.8 2.7 (0.7)
Skagerak Fm, part 3	22	70	2.9-5.8 4.3 (0.8)	2.3-5.1 3.5 (0.7)	7.9-16.0 10.9 (1.8)	0.5-1.1 0.8 (0.2)	1.6-3.3 2.5 (0.4)	2.3-3.9 3.2 (0.3)
Skagerak Fm, part 4	23	104	2.3-4.4 3.2 (0.4)	1.3-3.7 2.3 (0.5)	4.3-10.6 7.8 (1.5)	0.5-1.2 0.7 (0.2)	1.8-3.4 2.5 (0.4)	2.4-4.2 3.5 (0.4)

Tønder - 4

	Unit no	Number of samples	K(%) Min-Max Mean(std)	U(ppm) Min-Max Mean(std)	Th(ppm) Min-Max Mean(std)	U/K Min-Max Mean(std)	Th/K Min-Max Mean(std)	Th/U Min-Max Mean(std)
Tertiary & Quaternary	24	69	1.0-2.6 2.0 (0.3)	1.1-4.2 2.6 (0.7)	3.9-12.7 8.4 (1.8)	0.6-2.1 1.3 (0.4)	2.6-6.7 4.3 (0.9(	1.3-6.8 3.4 (0.9)
Chalk	25	51	0.2-1.3 0.6 (0.3)	0.3-2.1 1.1 (0.5)	0.7-6.3 2.6 (1.5)	0.8-4.4 2.2 (0.8)	3.4-7.2 4.8 (0.8)	0.9-6.3 2.5 (1.0)
Vedsted Fm, clay part	26	7	0.9-1.9 1.6 (0.3)	0.5-2.6 1.9 (0.7)	3.9-9.6 7.8 (2.0)	0.6-1.5 1.1 (0.3)	4.2-5.2 4.9 (0.3)	3.3-7.7 4.6 (1.5)
Oddesund Fm	27	25	0.5-2.6 1.9 (0.5)	1.2-3.4 2.3 (0.5)	5.9-9.3 7.7 (0.7)	0.8-4.6 1.4 (0.8)	3.2-17.9 4.7 (3.1)	2.0-5.0 3.4 (0.6)
Tønder Fm	28	36	1.5-3.3 2.6 (0.4)	1.6-3.8 2.4 (0.4)	6.2-10.1 8.0 (1.1)	0.7-1.4 1.0 (0.2)	2.4-4.2 3.2 (0.4)	2.2-4.8 3.4 (0.6)
Falster Fm	29	34	1.1-2.7 1.7 (0.4)	1.4-3.6 2.0 (0.3)	4.3-7.3 5.4 (0.8)	0.7-1.8 1.3 (0.3)	2.7-4.0 3.3 (0.4)	1.6-4.0 2.7 (0.6)
Ørslev Fm	30	24	0.5-2.2 1.4 (0.5)	0.6-2.6 1.7 (0.6)	1.5-7.8 5.0 (1.9)	1.1-1.8 1.3 (0.2)	3.2-4.3 3.7 (0.3)	1.8-3.8 2.9 (0.5)
Bunter sandstone Fm	31	47	0.2-2.5 1.8 (0.7)	0.1-4.0 2.4 (1.1)	0.4-9.0 6.6 (2.7)	0.9-1.9 1.3 (0.3)	2.2-4.5 3.6 (0.4)	2.0-4.1 2.9 (0.6)
Bunter sandstone, part 1	32	22	0.3-2.5 2.1 (0.4)	0.4-4.0 3.1 (0.7)	1.0-9.0 7.9 (1.6)	1.0-1.9 1.5 (0.2)	3.1-4.2 3.7 (0.3)	2.0-3.5 2.6 (0.4)
Bunter sandstone, part 2	33	8	0.5-2.4 1.5 (0.7)	0.6-2.7 1.7 (0.8)	1.4-8.9 4.8 (2.8)	0.9-1.3 1.1 (0.1)	2.2-3.7 3.1 (0.5)	2.0-3.6 2.8 (0.5)

Tønder - 5

	Unit no	Number of samples	K(%) Min-Max Mean(std)	U(ppm) Min-Max Mean(std)	Th(ppm) Min-Max Mean(std)	U/K Min-Max Mean(std)	Th/K Min-Max Mean(std)	Th/U Min-Max Mean(std)
Tertiary & Quaternary	34	48	1.1-3.3 2.1 (0.4)	1.4-4.3 2.2 (0.5)	4.2-11.1 8.1 (1.7)	0.7-1.3 1.1 (0.3)	2.4-5.2 4.0 (0.5)	1.8-6.2 3.9 (1.1)
Chalk	35	21	0.2-1.7 0.7 (0.4)	0.2-1.4 0.9 (0.5)	0.4-7.7 2.9 (1.7)	0.5-2.1 1.4 (0.4)	2.0-5.5 4.0 (0.8)	1.1-9.0 3.4 (1.8)
Vedsted Fm, clay part	36	6	1.7-2.1 2.0 (0.1)	1.8-2.4 2.1 (0.2)	8.0-10.0 9.4 (0.7)	0.9-1.3 1.1 (0.1)	4.6-5.0 4.8 (0.2)	3.7-5.3 4.4 (0.5)
Oddesund Fm	37	31	0.6-2.7 2.1 (0.5)	1.2-3.1 2.4 (0.5)	5.3-12.5 8.2 (1.5)	0.8-4.2 1.3 (0.7)	3.1-18.0 4.6 (3.1)	2.4-5.4 3.6 (0.7)
Tønder Fm	38	39	1.6-3.2 2.7 (0.4)	1.5-3.2 2.3 (0.4)	5.4-10.7 8.3 (1.4)	0.6-1.2 0.9 (0.2)	2.6-3.5 3.1 (0.2)	2.8-4.9 3.7 (0.5)
Falster Fm	39	35	0.7-2.6 1.5 (0.4)	0.8-2.8 1.8 (0.4)	2.4-7.3 5.1 (0.9)	0.6-1.7 1.2 (0.3)	2.7-4.0 3.3 (0.3)	2.0-4.9 2.8 (0.6)
Bunter sandstone Fm	40	47	1.0-2.4 2.0 (0.3)	1.3-5.0 3.2 (0.8)	3.1-9.8 7.4 (1.4)	0.9-2.3 1.5 (0.3)	2.4-4.2 3.6 (0.4)	1.7-3.1 2.4 (0.4)
Bunter sandstone, part 1	41	23	2.0-2.4 2.2 (0.1)	2.8-5.0 3.9 (0.6)	7.2-9.8 8.4 (0.7)	1.3-2.3 1.7 (0.3)	3.4-4.2 3.8 (0.2)	1.7-3.1 2.2 (0.4)
Bunter sandstone, part 2	42	10	1.6-2.1 2.0 (0.2)	1.7-2.9 2.3 (0.4)	4.6-8.0 6.2 (1.2)	0.9-1.4 1.2 (0.2)	2.4-3.8 3.1 (0.5)	1.8-2.9 2.6 (0.3)

Risø National Laboratory **Risø – M – 2646**

Title and author(s)

GAMMA-RAY ANALYSIS FOR U, TH AND K ON BULK CUTTING SAMPLES FROM DEEP WELLS IN THE DANISH SUBBASIN AND THE NORTH GERMAN BASIN:

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Date April 1987

Department or group

Groups own registration number(s)

Project/contract no.
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Agreement 4124/CF

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Abstract (Max. 2000 char.)

A total of 1329 bulk cutting samples from deep wells in Denmark were analysed for U, Th and K by laboratory gamma-ray analysis. Contamination of the samples by drilling mud additives, mud solids and fall down was studied by means of a wash down experiment and by comparison with the total gamma-ray response from wire-line logging. It is concluded that the inorganic geochemistry on bulk cutting samples must be applied with great caution. The data are useful for geochemical characterization of well sections and for regional geochemical correlation.

Radioelement abundance logs and radioelement ratio logs are presented from 3 wells in the Danish Subbasin and 2 wells in the North German Basin. The radioelement geochemistry is discussed for the successive lithostratigraphical units and a reference radio element profile is established for the central part of the

(Continued on next page)

Descriptors – INIS

DENMARK; DRILL CORES; ELEMENT ABUNDANCE; GAMMA LOGGING; GAMMA SPECTROSCOPY;GEOCHEMISTRY; POTASSIUM; STRATIGRAPHY; THORIUM; URANIUM

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Danish Subbasin. Finally, a model describing the relationship between common lithofacies and their U content and Th/U ratio is suggested. The model deliniates the depositional environment and the relative distances to the provenance areas.

It is concluded that

1) Uranium is mobile during deposition, but since then it is fixed by stable mineral phases at depth.

2) Thorium reflects source area characteristics and that any available ions are readily adsorped by clay minerals. Thorium anomalies may thus serve as lithostratigraphical markers.

3) Potassium occurs in unstable rock forming mineral phases. The present distribution is controlled not only by the clastic mineral assemblage, but also by the diagenetic processes through geologic time.

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